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LONG TERM OPTIMUM PERFORMANCE/CORROSION TESTS OF COMBUSTION MODIFICATIONS FOR UTILITY BOILERS

Host Site: Utah Power and Light Company
Hunter No. 2

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16. ABSTRACT Combustion modifications (e.g., low excess air firing, staged combustion) can decrease NOx emissions from coal-fired utility boilers. However, these operating conditions may affect the rate of tube wall corrosion by creating chemically reducing environments in the furnace. Therefore, this study was designed to measure boiler corrosion rates as well as the effects of certain combustion modifications (CM) for NOx control. This report deals with Boiler No. 2 at Utah Power and Light Co.'s Hunter Generating Station in Castle Dale, Utah. Initially, the boiler was characterized to determine the short term effects of CM on boiler emissions and performance. Later, NOx and other emissions were monitored continuously during several 30-day periods so that longer term operations could be evaluated. Finally, a study of corrosion rates inside the furnace helped to determine the corrosion effects of low-NOx operation. At Hunter No. 2, a special Low-NOx Concentric Firing System (LNCFS) was installed by Combustion Engineering, Inc. The LNCFS deflects some of the combustion air away from the fuel jets and toward the furnace walls to decrease both NOx emissions and corrosion effects. In these tests, the LNCFS together with other combustion controls were able to decrease full-load NOx emissions durboth normal long term operation and shorter well-controlled tests using extreme CM

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Corrosion		Low NOx	11M	
Boilers		Combustion Modifications	13A	
Emission			14G	
Combustion Control			21B	

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PREFACE

In response to increasing concern over gaseous pollution from coal-fired power plants, the United States Environmental Protection Agency (EPA) has supported various research programs aimed at the control of oxides of nitrogen (NO_x) emissions. NO_x, (especially NO_2) a yellow-brown gas, is a component of photo-chemical smog, an eye and lung irritant and a precursor to acid rain.

Laboratory and pilot scale programs have resulted in some novel methods for NO_x abatement. However, there was a need to determine whether these new methods could be applied to full scale units without causing adverse safety or operating problems.

In this respect, the authors and sponsors of the work reported here gratefully acknowledge the owners, operators and staff of Utah Power and Light Company (UP&L) for their progressive attitude in hosting these tests. With UP&L's cooperation, the host site, Boiler No. 2 at UP&L's Hunter Generating Station in Castle Dale Utah, was specially modified and tested during the 2-3 year research program.

Because of the research nature of the program, considerable instrumentation and highly skilled manpower, not practical for normal day-to-day operation, was employed during the test period. This extra attention to boiler operations allowed the boiler to be operated for short periods of time, in modes that would not ordinarily be possible. Further, because of the wide variety of operating conditions that were explored during these tests, many cause-and-effect relationships were established more clearly than would have been possible over the normal range of boiler operations. The data also helped to more clearly define the acceptable range of normal operations. Finally, it is expected that the data will aid scientists and engineers who seek to improve boiler designs.

It should be emphasized that much of the data reported were obtained at conditions that are clearly not recommended for long term operation. Such data (e.g., at conditions of high CO) have been clearly identified throughout the report.

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ABBREVIATIONS AND SYMBOLS*

ACF	Actual Cubic Feet
ACM	Actual Cubic Meters
APTI	Air Pollution Training Institute
AUX X	Auxiliary Air Compartment No. X
Btu	British Thermal Unit
C-E	Combustion Engineering, Incorporated
CEM	Continuous Emission Monitor (For Gaseous Emissions)
CM	Combustion Modification
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRT	Cathode Ray Tube (i.e., TV Screen)
DELTA P	Windbox to furnace differential pressure
DSCF	Dry Standard Cubic Feet (at STP)
DSCM	Dry Standard Cubic Meters (at STP)
EAD	Equivalent Aerodynamic Diameter (For Small Particles in a Gas Stream)
EPA	Environmental Protection Agency
ER&E	Exxon Research and Engineering Company
ESP	Electrostatic Precipitator
FAD	Fuel Air Dampers (Percent Open)
IWG	Inches of Water (Gauge Pressure)
LEA	Low Excess Air
LNCFS	Low-NO_x Concentric Firing System
MW_e	Megawatts, Electric
MW_{th}	Megawatts, Thermal

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*Other terms are covered in Section V ("Nomenclature") of this part (Part A) of this report.

Special Abbreviations Used in Parts C and D of this report may be found on Page 60.

ABBREVIATIONS AND SYMBOLS* (Cont'd)

ng/J	Nanograms per Joule
NO	Nitrogen (Mon)Oxide
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen ($NO + NO_2$)
NSPS	New Source Performance Standard
NTIS	National Technical Information Service
O_2	Oxygen
OFA	Overfire Air
OFAD	Overfire Air Dampers (Percent Open)
OFAT	Overfire Air Tilt (Degrees -- Up is positive)
PDSA	Pheno Disulfonic Acid (Method 7 for NO_x)
PM	Particulate Matter
PS	Performance Specification (usually refers to CEMs e.g., PS1 is for opacity monitors)
PSD	Particle Size Distribution
PSIA	Pounds per Square Inch (Absolute Pressure)
PSIG	Pounds per Square Inch (Gauge Pressure)
QA/QC	Quality Assurance/Quality Control
SCF	Standard Cubic Feet (at STP)
SCM	Standard Cubic Meters (at STP)
SI	System International (Metric System of Measurement Units)
SO_2	Sulfur Dioxide
STP	Standard Temperature (20°C or 68°F) and Pressure (1 Atm.)
UP&L	Utah Power and Light Company
US EPA	United States Environmental Protection Agency
UT	Ultrasonic Thickness

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*Other terms are covered in Section V ("Nomenclature") of this part (Part A) of this report.

Special Abbreviations Used in Part C and D of this report may be found on Page 60.

ABBREVIATIONS AND SYMBOLS*

WSCF	Wet Standard Cubic Feet (at STP)
WSCM	Wet Standard Cubic Meters (at STP)
vppm	Parts-per-Million (by Volume)

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*Other terms are covered in Section V ("Nomenclature") of this part (Part A) of this report.

Special Abbreviations Used in Part C and D of this report may be found on Page 60.

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SUMMARY

For coal-fired utility boilers, NO_x emission regulations can often be met by combustion modification (CM) techniques such as low excess air (LEA) firing. However this method can lead to chemically reducing atmospheres in certain regions of the furnace which, in turn, can cause increased corrosion on the fireside of the furnace tube walls. Under this contract, performance and corrosion were studied at several coal-fired utility boilers with a separate report issued on each. This report deals with a study performed at Utah Power and Light Company's Hunter Generating Station, Boiler No. 2, in Castle Dale, Utah. At the Hunter Generating Station, a novel firing system design called a "Low-NO_x Concentric Firing System" (LNCFS), developed by Combustion Engineering, Inc., was studied. The LNCFS had the potential to decrease NO_x emissions in tangentially fired boilers without causing increased corrosion. This was done by diverting some of the combustion air away from the fuel jets and towards the boiler walls. The several phases of the study included boiler characterization (both before and after installation of the LNCFS), thirty-day continuous emission studies, and corrosion testing. Some of the key accomplishments of the program are discussed below.

Boiler Characterization

Combustion modifications can be accomplished by both operational changes (e.g., the use of overfire air), and hardware changes (e.g., installation of LNCFS). At the Hunter No. 2 Unit, 387 short-term (~1/2 hour) tests were performed under this program in order to evaluate the effects of various combustion controls on NO_x emissions both before and after installation of the LNCFS.

- Baseline (Pre-Modification)

In the "as found" condition, NO_x emissions were about 460 vppm (0.63 lb/MBtu, 270 ng/J) at typical full load conditions (4.5% O_2, no overfire air, and burner tilts ±5 degrees from horizontal). It was found, during these early characterization tests, that by using the existing boiler controls (i.e., no hardware changes), that full load NO_x emissions could be decreased by about 30% to approximately 320 vppm (0.44 lb/MBtu, 188 ng/J) without adversely affecting boiler performance or operability. This was accomplished by decreasing excess oxygen (to 3.5%), opening the overfire air dampers, and adjusting the overfire air nozzle tilts.

- Post-Modification

Installation of the LNCFS involved certain hardware modifications to the boiler and produced even greater NO_x reductions than were seen during the baseline (pre-modification) tests. For example, under extreme low-NO_x conditions (not recommended for long-term operation because of boiler operability problems) NO_x emissions of 180 to 200 vppm (0.25 to 0.27 lb/MBtu, 106 to 118 ng/J) were possible when at slightly less than full load. It should be reemphasized that, as explained in the preface to this report, these low NO_x values we obtained during short (20-30 minute) tests while employing an exceptional amount of instrumentation and highly skilled manpower to monitor boiler operations which were maintained for the brief time of the tests. These data are useful from a research point of view to help establish cause-and-effect relationship more clearly than would be possible during normal operations. They also helped to establish a comfort range surrounding the normal operating envelope. The NO_x levels measured during these well-controlled tests fulfilled the short term, full load, optimized performance goal of 0.30 lb/MBtu (129 ng/J) for this boiler, and also appear to be approaching a low-NO_x threshhold achievable for this type of boiler, fuel type, and fuel system design.

Over the entire range of boiler operations, short term tests demonstrated the ability to achieve average NO_x levels of about 265 vppm (0.36 lb/MBtu, 156 ng/J). However, this average was achieved by using an exceptional degree of manual boiler control. In comparison, during the modification 2 test period, an average NO_x level of 0.41 lb/MBtu (176 ng/J) was demonstrated during the four 30-day monitoring tests (see Part E), which incorporated a more modest (typical) degree of boiler control.

Other recommended combustion modifications (CMs) and their effects are discussed in the body of this report.

Thirty-day Continuous Emission Monitoring (CEM) Tests

Four times, during the Modification 2 period of this program, flue gas emissions (NO, CO, CO_2 and O_2) at the Hunter No. 2 Unit were monitored continuously for thirty days using continuous emission monitors (CEMs). This work provided a better understanding of the abilities, problems, and performance limitations that might be associated with CEMs in similar situations, and also permitted an evaluation of boiler emissions over normal load cycles for longer periods than were possible during the characterization tests performed earlier.

Results show that for the four tests, NO_x emissions (as NO_2) averaged about 176 ng/J (0.41 lb/MBtu) (well below the 1979 NSPS limit of 260 ng/J [0.60 lb/MBtu] for bituminous coal) with a maximum daily average (for any day of the four tests) of about 240 ng/J (~0.56 lb/MBtu). The extractive type CEM used in these tests provided quality data for each test as verified by use of EPA reference methods. However, the continuance of high quality data required regular maintenance and calibration of the CEM system.

Corrosion Tests

In order to more fully evaluate the longer term effects of low-NO_x operation, corrosion testing was performed by two different methods in order to measure the metal wastage rate on the fire side of the tube walls inside the furnace. In the corrosion probe method, temperature controlled samples of boiler wall material were inserted into the furnace for respective time periods of 30, 300 and 1,000 hours. After removal from the furnace, their weight loss was indicative of the boiler walls' short-term corrosion rate. The other method was an ultrasonic pulse echo method. In this method, boiler tube wall thicknesses were measured on two different occasions (after baseline, and again after Modification 2 testing) two years apart (during scheduled outages) in order to determine long term corrosion rates at hundreds of locations inside the furnace.

The tests showed, as expected, that corrosion rates slow down with time from about 100 mills per year (determined from the 30 hour test data) to less than one mill per year (based on the long term [2 year] ultrasonic measurements). Because each tube has a nominal wall thickness of ~1/4 inch, the corrosion rates measured under this program (less than 1 mil [<0.001 inch] per year on the average) would not be expected to reduce this boiler's useful life below the thirty or more years normally expected.

PART A

PROGRAM INTRODUCTION, APPROACH AND DETAILED DESCRIPTION OF HUNTER NO. 2

I. INTRODUCTION

Tangentially coal-fired utility boilers account for about half the steam-electric capacity and about 40 percent of the NO_x emissions generated in the U.S. by coal-fired utility boilers. Combustion modification (CM) technology for decreased NO_x emissions from tangentially fired boilers utilizes overfire air (this technique is also called staged combustion). CM is capable of meeting the current New Source Performance Standard (NSPS) of 0.6 and 0.5 pounds of NO_x per million Btu fired (lb/MBtu) for bituminous and subbituminous coals, respectively. However, it appeared that overfire air technology alone would not be capable of meeting future EPA research goals for NO_x of approximately 0.3 lb/MBtu. EPA-sponsored low-NO_x coal burner development programs for wall-fired boilers were already underway and showed promise of meeting the research goal. A field evaluation of a low-NO_x coal burner on a wall-fired boiler was being formulated. Development of advanced low-NO_x burners for tangentially fired boilers lagged the wall-fired burner development by several years primarily due to R&D funding constraints.

In response to this technology gap, EPA's Industrial Environmental Research Laboratory at Research Triangle Park, NC, awarded Contract 68-02-1885 to the Acurex Corporation in September 1978 for pilot-scale development of low-NO_x firing systems applicable to tangentially coal-fired utility boilers. A 293 kW_{th} (1×10^6 Btu/hr) pilot-scale system was used to develop a firing method which ultimately achieved low NO_x by directing the fuel and a fraction of the secondary combustion air into the center of the furnace, with the balance of the secondary combustion air directed horizontally towards the furnace walls. This separation of fuel and air created a fuel-rich zone in the center of the furnace where NO_x production was minimized. Under these conditions, NO_x emissions were controlled to a level of 0.25 lbs NO_x per million Btu--a reduction of 58 percent relative to the conventional mode of tangential firing. An additional benefit of this combustion modification is that it places a blanket of air along the furnace walls which reduces the potential for waterwall slagging and fireside corrosion.

During this same time frame, Combustion Engineering, Inc. independently conducted field tests of a similar low-NO_x concentric firing system (LNCFS) at the 61 MWe Whitewater Valley Unit No.2 of Richmond (Indiana) Power and Light Company. A variety of air injection angles (offset angles) were evaluated. NO_x reductions of up to 40 percent were achieved at full load using simulated overfire air operation along with secondary air injection angles of 22 and 35 degrees offset from the fuel firing angle.

Based on these successful pilot-scale and field trials, EPA Contract 68-02-3655 was awarded to Combustion Engineering, Inc., in September 1980 for the design, fabrication, and installation of a low-NO_x firing system on the 425 MWe Hunter Unit No. 2 of Utah Power and Light Company. The system became operational in October 1981, less than 13 months after the contract was signed.

Performance and emissions testing of this low-NO_x firing system at Hunter Unit 2 together with an assessment of waterwall corrosion rates was conducted by Exxon Research and Engineering Company under EPA Contract 68-02-2696 with support from Combustion Engineering. Pre-modification tests were conducted to establish baseline performance and emission levels of the unit. Extensive post-modification tests were conducted to determine performance and emission levels with the low-NO_x firing system. On-site performance testing was conducted in several phases over a period of about two and one half years. After optimization of the system, full-load NO_x emissions were controlled to a level of about 0.26 lb/MBtu (112 ng/J)--a reduction of 60 percent from previous operating levels on this unit. These levels fulfilled the short term, full-load, optimized, performance goal of 0.30 lb/MBtu (129 ng/J) for this boiler. Furthermore, the results of four 30-day continuous NO_x monitoring tests performed on this unit averaged 0.41 lb/MBtu (176 ng/J) over a load range of 200 to 360 MWe (about 50 to 90 percent of full load).

On this project, C-E and Exxon acted as a team, each under its own EPA contract. Consequently, Exxon and C-E have shared some data but are each responsible for their own separate reports. The C-E report discusses the mechanics, construction, and theory of the LNCFS in detail while this report focuses on the boiler emissions and tube wall corrosion measurements. Some information provided by C-E (boiler description, windbox modifications, etc.) is discussed briefly in this report. However, a more extensive presentation of these items can be found in the C-E report.

II. PROGRAM APPROACH

The several tasks of the test program included:

- Boiler Characterization
    - Baseline (Pre-Modification)
    - Post-Modification (LNCFS Modifications 1, 2 and 3)
- Corrosion Testing by
    - Probes

  - Wall measurements

- 30 day continuous NO_x monitoring (Four 30-Day Tests)

A. Boiler Characterization

In the boiler characterization phase of the work, NO_x emissions and other boiler characteristics were measured both before and after the LNCFS modifications. Also the effects of various boiler combustion modifications which did not require hardware changes were assessed, including an evaluation of their ability to control NO_x emissions without causing short-term adverse side effects (such as increased slagging). Of special interest was the effect of the LNCFS modifications on NO_x emissions and boiler operability.

Flue gas emissions (CO_2, CO, O_2, NO, NO_x, etc.) were monitored periodically. Also, furnace gas composition (CO and O_2) was monitored occasionally at various locations along the furnace walls in order to assess the air blanketing effect of the LNCFS offset air deflectors (see Sections III and IV of this report) and to identify locally corrosive environments for further study.

Finally, because certain NO_x controls could affect fly ash resistivity and ash particle size distribution (which could, in turn, affect the performance of the electrostatic precipitator [ESP]) the characterization tests included a short period during which ESP performance was measured. The ESP performance test included measurements of particulate grain loading in the flue gas at the ESP inlet and outlet, and particle size distribution (PSD) measurements at the ESP inlets.

B. Corrosion Tests

Historically, one of the easiest and most effective combustion modifications used to decrease NO_x emissions has been low excess air (LEA) firing. However, decreasing the amount of combustion air could lead to a chemically reducing atmosphere in certain regions of the furnace which could cause increased corrosion rates on the furnace walls. The LNCFS with its offset air vanes diverts some of the combustion air towards the furnace walls, thus partially blanketing them against the possibly corrosive low excess air environment. Corrosion testing was initiated at the conclusion of the baseline (pre-LNCFS) boiler characterization tests. Two methods (corrosion probes, and ultrasonic wall thickness mapping) were used to evaluate fireside corrosion of boiler water tube walls within the furnace.

1. Corrosion Probes

Corrosion probes were used to evaluate short term corrosion effects. In this method, pieces of wall tube type materials (corrosion coupons or test rings) were inserted into the furnace through inspection doors for approximately 30, 300 and 1000 hours and then weighed to determine the rate of metal loss. This non-destructive test method gives an economically attractive alternative to more direct (and sometimes destructive) test methods which require entry into the boiler to measure actual wall losses.

2. Wall Thickness Mapping

The wall thickness mapping method involved ultrasonic thickness (UT) measurements (echo sounding) of all walls from inside the furnace at hundreds of points. The first set of such wall measurements occurred during the outage in which the first LNCFS modification was installed (September 1981). The second set of measurements was performed about two years later (February 1984) during the outage in which the third LNCFS Modification was installed.

C. 30-Day Emissions Tests

Four times during the two year corrosion exposure period, NO_x and other flue gases were monitored continuously for 30 days using an extractive continuous emissions monitoring (CEM) system. The 30-day CEM tests provided a better quantification of flue gas emissions over normal boiler load cycles and for longer periods of time than was possible during the characterization tests. These tests also gave the researchers an indication of how a CEM may be expected to perform (reliability, accuracy, maintenance needs, etc.) in other similar situations.

III. BOILER DESCRIPTION

Hunter No. 2 is the second boiler constructed at Utah Power and Light (UP&L) Company's Hunter Generating Station in Castle Dale, Utah. Designed by Combustion Engineering, Inc. (C-E), it burns about 200 tons per hour of locally mined coal to produce about 425 MWe of electric power. It was designed with the flexibility to use combustion modifications (CM) (such as overfire air [OFA]), if necessary, for compliance with the applicable New Source Performance Standard (NSPS) for NO_x emissions.

The Hunter No. 2 Unit uses tangential firing in a single-compartment, balanced-draft, water-wall boiler, to produce about three million pounds of super-heated steam (1005°F, 2645 psi) per hour. This steam drives a turbine to produce electric power for UP&L's residential and industrial customers in Utah and vicinity.

Coal enters the plant by conveyor belts feeding five storage silos. The silos can support about six to eight hours of full load operation. From each silo, the coal drops to a variable feed rate controller, and then to a mill where it is pulverized into a fine powder (one feeder and mill for each silo).

Primary air (about 20% or less of the total combustion air) enters the mill and pneumatically conveys the pulverized coal dust into the furnace. Each of the five pulverizers feeds four burners at a single elevation (one burner in each of the four corners of the furnace). Any one or more of the five elevations of burners (four burners per elevation, 20 burners total) can be shut down by stopping the mill and its associated feeder.

As the fuel leaves the burner nozzle and enters the furnace, secondary and tertiary air sources (fuel air and auxiliary air, respectively) mix with it (the fuel), and once exposed to the hot gases inside the furnace, the fuel quickly reaches its ignition temperature and combustion is sustained.

The burner and air nozzles are designed to produce a cyclonic vortex (counter-clockwise as seen from above) within the boiler by aiming each burner tangent to an imaginary circle in the center of the boiler. The cyclonic fireball can be moved up and down by tilting the burner nozzles to optimize heat transfer utilization and steam temperature control.

Air enters the boiler by any of four ways, all located in the corners of the furnace. Primary air is used to blow the pulverized coal into the boiler. Fuel air enters through ports surrounding each fuel nozzle. Auxiliary air enters through ports located between each adjacent pair of burners as well as below the bottom bank and above the top bank of burners. Finally, overfire air (OFA) enters at elevations above the top auxiliary air compartments. The two levels of OFA nozzles can be manually tilted up or down independent of the burner tilts, to control the separation between the overfire air and the flame.

For each corner of the boiler, all air (except for the primary air) is supplied by a single pressurized manifold (called the windbox). A sketch of the windbox is shown in Figure A-1. The distribution of the windbox air to the various ports feeding air to the furnace is controlled by a series of dampers. Each air path has its own damper system. The position of these dampers is usually controlled remotely (from the control room) except for the bottom auxiliary air dampers which are controlled manually by local controls at each respective damper location. During this test program, certain modifications were made to the boiler's windbox and associated systems through which combustion air enters the boiler. These are discussed below.

Concerning the percentage of coal which is not combusted (ash), the densest portion (bottom ash) falls into a water-filled hopper at the bottom of the furnace where it is quenched and periodically flushed to a settler. The lighter ash (fly ash) particles are carried by the combustion gases to the electrostatic precipitator (ESP) where most particles are removed from the gas before it passes through the scrubber (for SO_2 control) and is exhausted through the dedicated stack. The dry, powdery fly ash catch in the ESP is emptied from the ESP hoppers periodically by a vacuum system. Other smaller amounts of intermediate size fly ash particles are collected in any of several hoppers between the furnace and the precipitator.

The gaseous combustion products pass through a series of heat exchangers where energy is transferred to the steam being produced and/or to the incoming air.

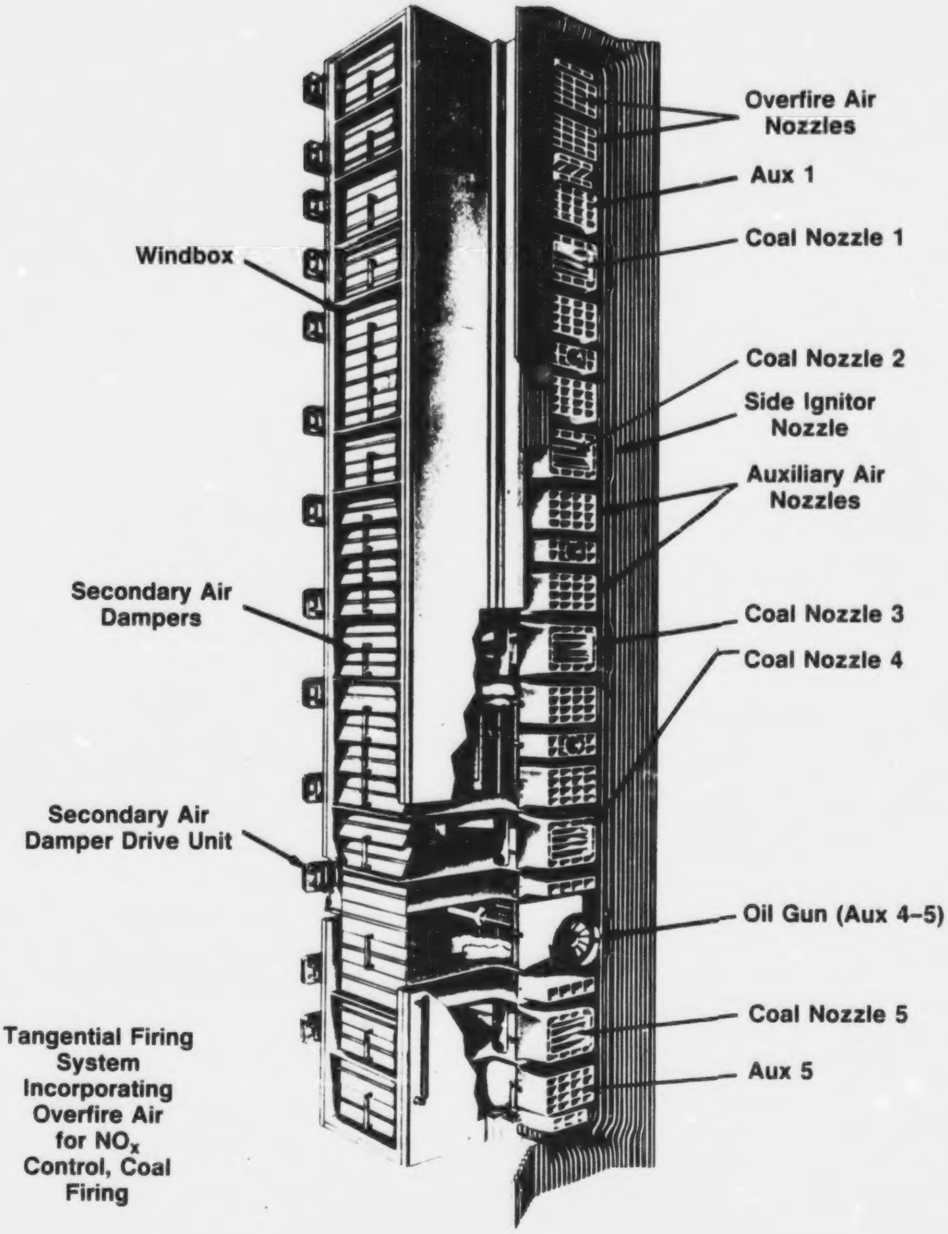
Overfire Air Nozzles
Aux 1
Coal Nozzle 1
Windbox
Coal Nozzle 2
Side Ignitor Nozzle
Auxiliary Air Nozzles
Secondary Air Dampers
Coal Nozzle 3
Coal Nozzle 4
Secondary Air Damper Drive Unit
Oil Gun (Aux 4–5)
Coal Nozzle 5
Aux 5
Tangential Firing System Incorporating Overfire Air for NO_x Control, Coal Firing

Figure A-1
Hunter Unit No. 2
Windbox Design

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IV. WINDBOX MODIFICATIONS AND THEORY

The Low-NO_x Concentric Firing System (LNCFS) tested under this program was developed for applications in tangentially fired steam generators. The LNCFS is designed to limit NO_x emissions by controlling the mixing of the fuel and the combustion air. This is achieved by directing the auxiliary air away from the center of the furnace (away from the fuel) and towards the walls to create a fuel-rich zone near the burners thus requiring more time (and space) for complete burnout as explained in the following paragraphs.

A. NO_x Mechanisms and Fuel Effects

Levy, et al.[A1] stated, that "the formation of nitrogen oxides during coal combustion is a complicated process involving contributions both from the fixation of atmospheric nitrogen (thermal-NO_x) as well as from the oxidation of nitrogen bound chemically in the fuel (fuel-NO_x)." The formation of nitric oxide via the thermal fixation of atmospheric nitrogen has been shown to be adequately represented by the highly temperature dependent chemical reaction of the Zeldovich mechanism, where the rate of formation is exponentially dependent on temperature and is proportional to the square root of oxygen concentration. Therefore, reducing the amount of oxygen available to the fuel and reducing the combustion temperature, are effective methods of controlling NO_x formation via the thermal mechanism.

Although only a fraction of the fuel-nitrogen is converted to NO_x, fuel-NO_x can represent a major fraction of the total NO_x formed when firing a high nitrogen content coal in a conventional steam generating unit. In a tangentially fired unit, fuel-NO_x can account for 30 to 55% of the total NO_x emissions for low moisture, high rank coals such as the high volatility, bituminous Utah coals. Thus, in pulverized coal firing, fuel nitrogen conversion is an extremely important source for NO_x formation.

Along with fuel-nitrogen, the coal oxygen to coal nitrogen ratio (O/N) has also been shown to have a significant effect on fuel-NO_x formation. In a diffusion flame, where the combustion air is gradually entrained along the length of the flame, the lower limit of NO_x emission attainable may be controlled by the presence of the oxygen and the nitrogen contained in the coal itself. On a tangentially fired unit, the pulverized coal is conveyed from the mills to the furnace in an air-stream with typical air-to-coal ratios of 1.5 to 2.0 pounds of air per pound of coal. Since this stream represents about 15 to 20 percent of the total combustion air, oxygen contained in the coal itself can represent a significant source of oxygen in the early stage of devolatilization and combustion. For a high oxygen Western subbituminous coal, the coal oxygen can constitute up to a third of the total available oxygen in the mill air/pulverized coal stream. Additionally, the coal-bound oxygen is in more intimate contact with the coal-bound nitrogen. Marshall and Selker[A2] have shown that the percentage of fuel-nitrogen that is converted to NO_x begins to increase substantially when O/N ratios increase above ~9.0. While fuel-nitrogen and coal O/N ratio have not been evaluated in this study, these parameters are reported in Appendix VI (Part J) to demonstrate that the variability in coal properties over the two and one half year test program may be somewhat responsible for variations in test results.

In addition to fuel-nitrogen and coal O/N ratios, coal ash characteristics also have an effect on NO_x formation. Various parameters, including the gravity fractionation and acetic acid soluble measurements along with more conventional acid/base, iron/calcium, silica/alumina ratios and ash fusibility measurements are important when evaluating the slagging propensity of a particular ash. If the composition and distribution of mineral matter combined with local stoichiometries and gas temperatures results in a sufficiently sintered or molten deposit a significant layer of ash can be formed on the tube walls. As the deposit builds up, the insulating effect of the ash will reduce the tube wall heat transfer rate, thereby causing an increase in the furnace combustion temperature. As a result, thermal-NO_x formation will increase. Due to the complexity of analysis, the effects of coal ash properties on NO_x levels were not evaluated in this study. (However, ash and fuel analyses may be found in Appendix VI [Part J].) An indirect effect of slag (ash) buildup was evaluated through the parameter burner (nozzle) tilt. In the Hunter Unit No. 2, burner tilts automatically compensate for increasing wall slag and load reductions. Therefore, for constant load operation, variations in NO_x levels with changing burner tilts were actually indicative of overall ash effects or NO_x levels.

B. Burner Design Theory

While the actual chemical reaction mechanisms for NO_x formation from coal combustion are very complex, the bases for low-NO_x operation and low-NO_x burner design are typically based on a simple combustion model. In this model, combustion of pulverized coal occurs in three main stages: evolution of the volatile components or devolatization, followed by homogeneous volatile combustion, and finally, heterogeneous combustion of the residual char. Although the stages may overlap, char combustion is generally of much longer duration than volatile combustion since very fine coal particles can begin to burn heterogeneously in the early devolatilization stage. Based on this model, the conversion of coal-nitrogen to NO_x can, therefore, also be regarded as a three-stage process: coal-nitrogen devolatilization, volatile-nitrogen combustion (and NO_x formation), and char-nitrogen combustion (and NO_x formation). As such, the extent of devolatilization prior to ignition and the distribution of fuel-nitrogen between char and volatiles will strongly influence NO_x emissions.

The NO_x reduction strategy in staged combustion is to operate the first stage at high temperatures to increase devolatilization of the coal-nitrogen, and to operate this stage under fuel rich conditions. Under such conditions, axial flame combustors (e.g., tangentially-fired units) favor N_2 formation, and overall fuel-NO formation is reduced.[A3] The second combustion stage should be kept at an oxygen-rich condition and at a lower temperature in order to keep excessive carbon losses at a minimum, although this will cause some conversion of char-nitrogen to NO_x.

The two main low-NO_x operational changes performed at the Hunter boiler were the introduction of overfire air, and a reduction in excess air levels (evaluated as excess oxygen present in the flue gas). Overfire air usage diverts air from the burner zone to just above it, thereby creating vertical staging which causes reducing conditions in the burner zone. Decreased excess air levels cause further reducing conditions in the combustion zone. Excess air can be decreased to the limits imposed by CO emissions, carbon loss (on fly ash) and boiler operability.

The major hardware change instituted during this test program was the installation of the C-E Low-NO_x Concentric Firing System (LNCFS). The LNCFS was developed for applications in steam generators to minimize reducing environments along the boiler walls (for corrosion control), and to limit NO_x emissions (by aerodynamically controlling the mixing of the fuel and combustion air). In the design of the LNCFS, auxiliary air is directed tangent to an imaginary circle around the center of the furnace that has a larger radius than the typical tangential firing circle (see Figure A-2). In terms of corrosion control, this flow of auxiliary air is designed to blanket the furnace tube walls with a high oxygen gas stream to shield the walls from the main flame swirl and thus reduce slag buildup and boiler tube corrosion. Regarding NO_x reduction, the configuration of the LNCFS stabilizes the flame front. In addition, since a significant part of the combustion air is diverted from the flame swirl towards the boiler walls, the intial devolatilization period occurs in a localized fuel-rich environment.

The effectiveness of the LNCFS was previously demonstrated at the Acurex 293 kW_{th} (1.0 MBtu/hr) pilot-scale unit, and at the 61 MW_e C-E boiler (Unit No. 2) at the Whitewater Valley Station of Richmond (Indiana) Power and Light Co. In comparing the Hunter and Acurex units, naturally, scale-up differences are noticed. One of the purposes of the Hunter tests was to look for such scale-up effects. The Hunter unit has multiple elevations of burners (5) and thus, experiences multi-level burner effects not seen at Acurex. Also, because the LNCFS was installed on Hunter No. 2 as a retrofit, it was subject to certain constraints that might not be present in "grass-roots" systems. For example, due to operational considerations, the Hunter unit is not able to direct as great a percentage of total combustion air along the walls as the Acurex unit. Also, because of overfire air usage plus retrofit design (i.e., a common overfire air plus fuel air and auxiliary air windbox), the auxiliary air and fuel air velocities and/or flow rates may not yield sufficient air jet momentum at the Hunter unit to demonstrate the potential effectiveness of the LNCFS offset angle that might be achieved in grass-roots applications. Additionally, because the Hunter unit employs tiltable multi-level burners, overfire air and varying LNCFS offset angles, the

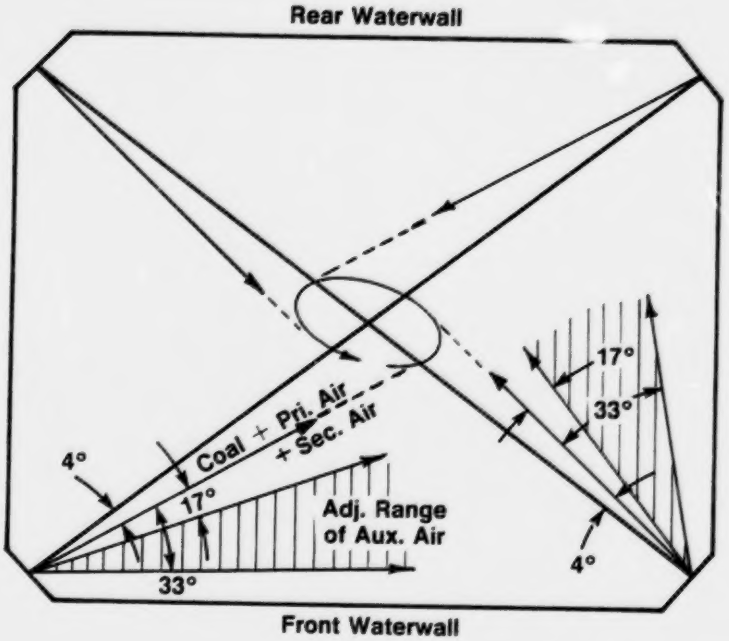
Rear Waterwall
Coal + Pri. Air
+ Sec. Air
4°
17°
33°
Adj. Range
of Aux. Air
17°
33°
4°
Front Waterwall

Figure A-2
Injection Angles for Fuel and Air, Hunter Unit No. 2
Utah Power and Light Company

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Hunter results may not be directly comparable with the Acurex results. Nevertheless, the modifications made on Hunter No. 2 afforded the researchers the best opportunity thus far available to study the LNCFS on a full scale unit.

The Hunter unit represents a system of very complex boiler aerodynamics and three dimensional staging. Because of this, the LNCFS was evaluated to determine the general effects of the hardware modifications on NO_x levels.

The evaluation also included a study of LNCFS offset angles to see if they caused distinct NO_x reduction trends, and to determine whether the offset angle effects, if any, were strongly related to other parametric effects.

At the Whitewater Valley unit, an LNCFS design similar to the Hunter unit was incorporated. The Whitewater Valley unit utilized three elevations of burners. However, since there was no provision for overfire air operation, overfire air had to be simulated by shutting off the top elevation of fuel, while keeping the top fuel air and auxiliary air compartments open. In comparing the Hunter and Whitewater Valley units the large scale-up difference should be considered. Also, the multi-level burner effects (two elevations) at Whitewater Valley are not as complex as at the Hunter unit (five elevations). In addition, the simulated overfire air operation at Whitewater Valley would not have decreased auxiliary air and fuel air velocities and/or flow rates to nearly the extent that they were decreased at the Hunter unit.

Three windbox hardware modifications were performed at the Hunter No. 2 Unit. In the first modification (Modification 1) conducted during the September, 1981 annual outage, the windbox was retrofitted with the LNCFS. Figures A-3 and A-4 show the

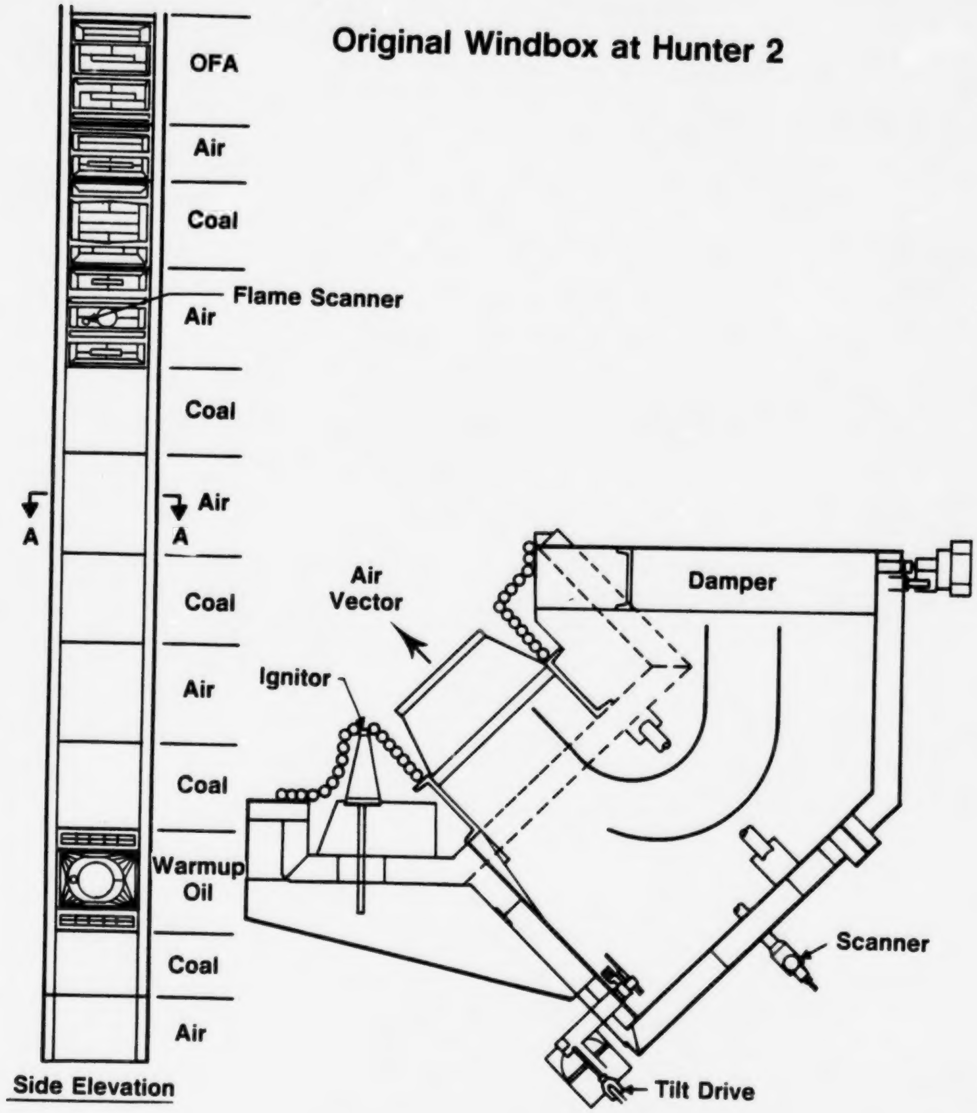
Original Windbox at Hunter 2
OFA
Air
Coal
Flame Scanner
Air
Coal
Air
A
A
Coal
Air
Coal
Warmup Oil
Coal
Air
Side Elevation
Air Vector
Damper
Ignitor
Scanner
Tilt Drive

Figure A-3
Plan View (A–A) of Original (Baseline) Auxiliary Air Compartment

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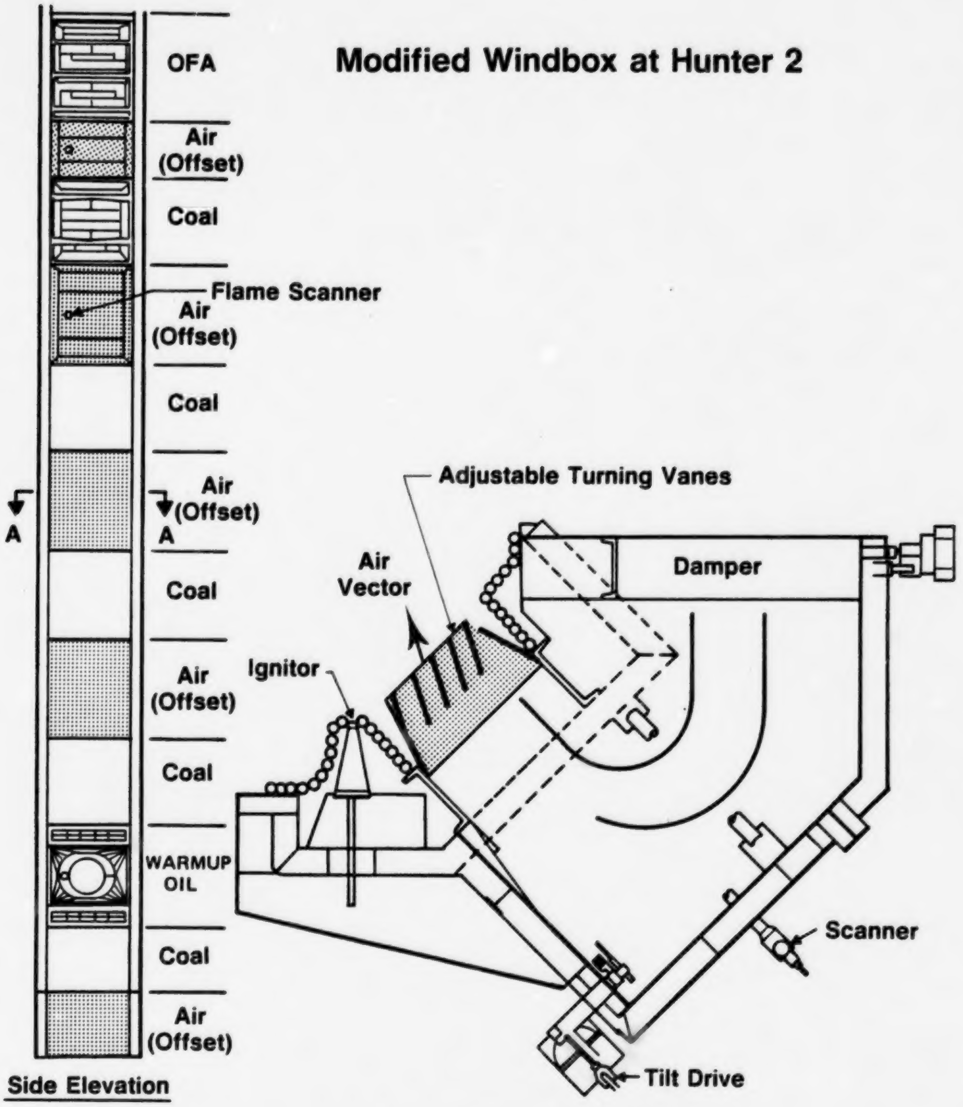

Modified Windbox at Hunter 2
OFA
Air (Offset)
Coal
Flame Scanner
Air (Offset)
Coal
A
A
Air (Offset)
Coal
Air (Offset)
Coal
WARMUP OIL
Coal
Air (Offset)
Side Elevation
Adjustable Turning Vanes
Air Vector
Damper
Ignitor
Scanner
Tilt Drive

Plan View (A–A) of Aux. Air Compart.

Figure A-4
Plan View (A–A) of
Modified Auxiliary Air Compartment

1084-5-568

original baseline and Modification 1 auxiliary air compartments. The three main auxiliary compartment elevations and the two half-size end auxiliary compartments were modified to accept horizontally adjustable offset air nozzle tips (see Figure A-5). The coal compartments were modified by reducing the free area available through which fuel air could pass (see Figure A-6). This forced more air through the offset auxiliary compartments and through the two unmodified overfire air compartments. This was done by removing the two fuel air nozzle tips located in each coal compartment and blocking off a majority (~67%) of the free area. The remainder of the fuel area was incorporated into a single, slightly larger, coal nozzle tip. The bluff body created by the blocking off of this free area enhances recirculation of the fuel-rich primary airstream and thus helps to create a close stable flame front.

Following the March 1982 series of post-modification testing, it was decided that a further optimization of the LNCFS was necessary to stabilize the flame front even closer to the coal nozzle tip than was possible with the bluff body created with the original LNCFS design. This goal (Modification 2) was accomplished by directing the fuel air away from the primary air and fuel jet with a divergent coal nozzle tip (i.e., a flame holder--see Figure A-7).

The windbox was further modified during the January, 1984 outage (Modification 3). The purpose of this modification was to reduce some of the boiler instability created by the synergistic combination of flame holders plus removal of too much fuel compartment free area. This was accomplished by shifting the blocking plates to effectively restore the blocked fuel compartments' free area and to block some auxiliary air compartments' free area. Table A-1 shows the relative compartmental free areas for each windbox modification. The flame holders were retained in Modification 3.

Low NO_x Concentric Firing System, UP&L Hunter No. 2

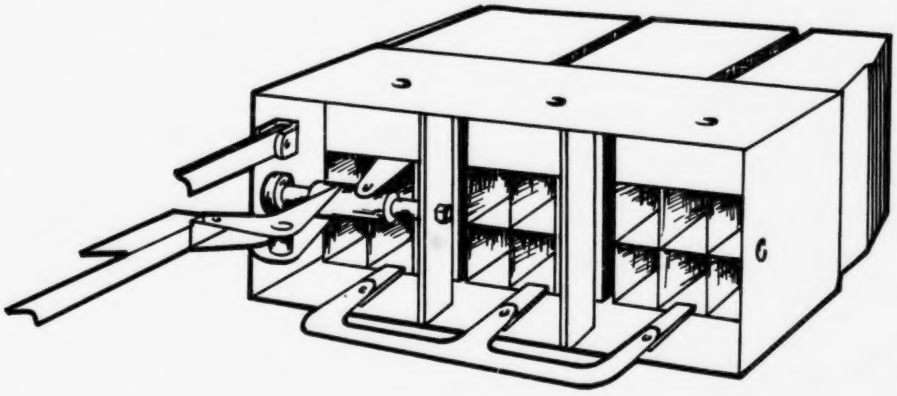
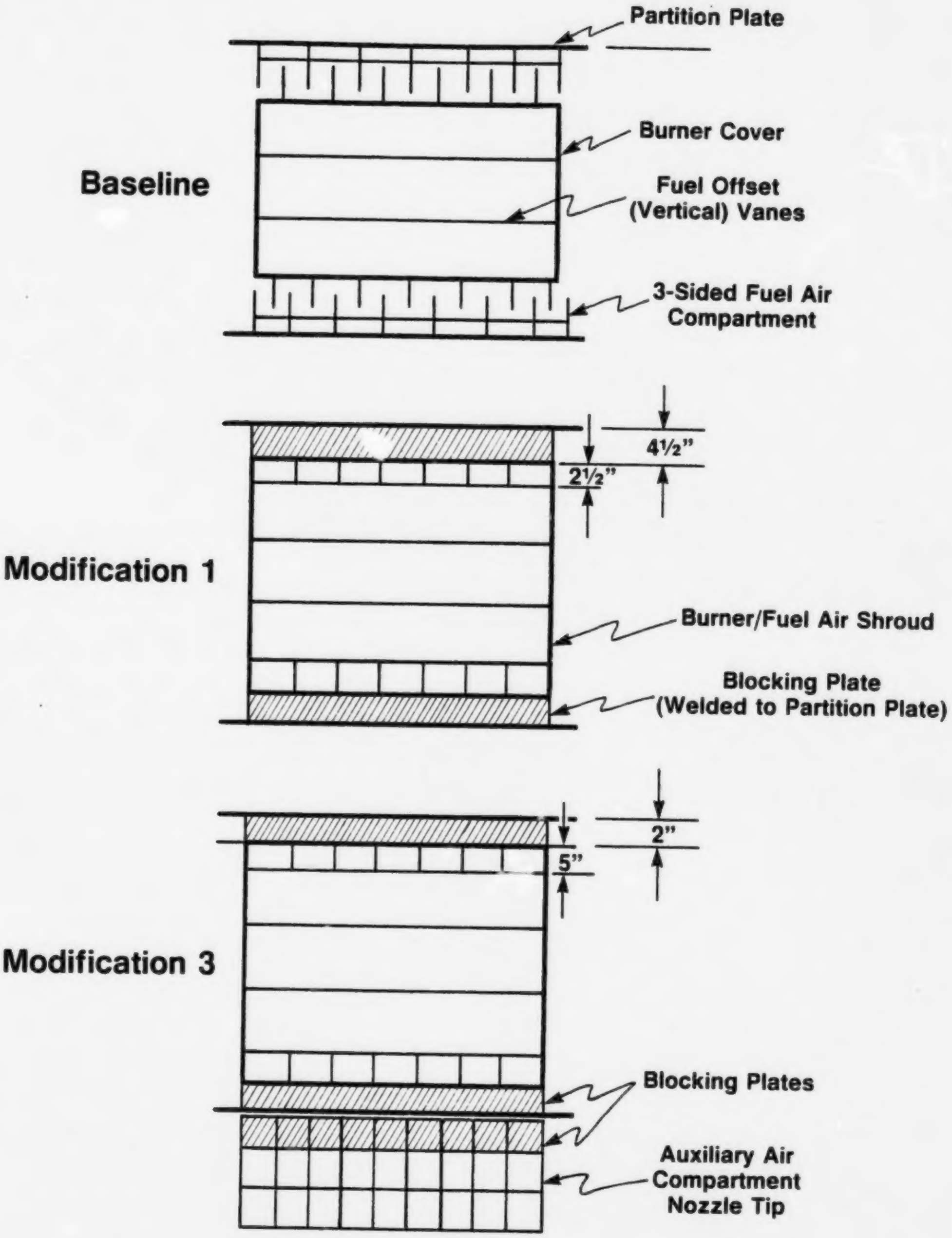


Figure A-5
Horizontal and Vertical Tilting Auxiliary Air Compartment Nozzle Tip for Tangential Firing

1084-5-569



Partition Plate
Burner Cover
Baseline
Fuel Offset (Vertical) Vanes
3-Sided Fuel Air Compartment
4½"
2½"
Modification 1
Burner/Fuel Air Shroud
Blocking Plate (Welded to Partition Plate)
2"
5"
Modification 3
Blocking Plates
Auxiliary Air Compartment Nozzle Tip

Figure A-6
Hunter Unit No. 2 Burner
and Air Compartment Modifications
(Frontal Views from Inside the Furnace)

1084-5-564

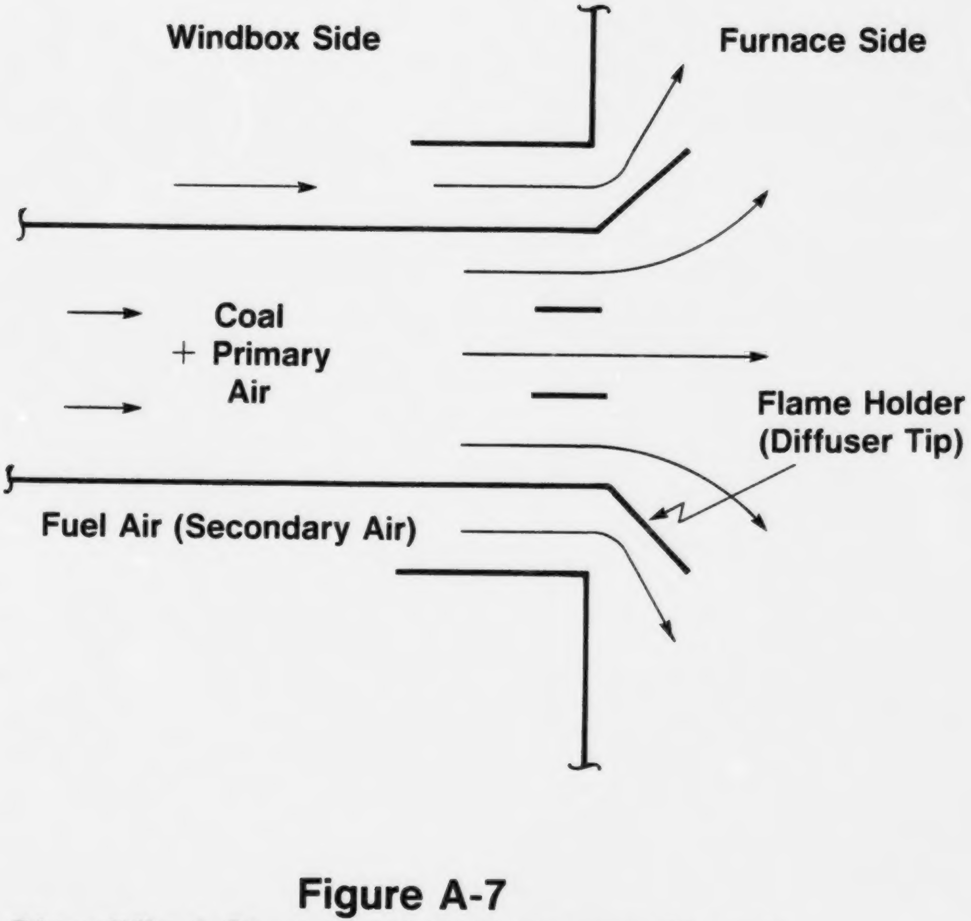

Windbox Side
Furnace Side
Coal
+ Primary
Air
Flame Holder
(Diffuser Tip)
Fuel Air (Secondary Air)

Figure A-7
Simplified Sketch of C-E Burner Nozzle
Showing "Flame Holders"

TABLE A-1

WINDBOX COMPARTMENT FREE AREA COMPARISON
LOW-NO$_x$ CONCENTRIC FIRING SYSTEM:
UTAH POWER AND LIGHT COMPANY - HUNTER UNIT 2

Designation	Compartment Height (inches)	Compartment Free Area (% of Total)		
		Design*	LNCFS*	Partially Restored
Overfire Air-2	21.25	6.95%	9.25%	7.68%
Overfire Air-1	21.25	6.95%	9.25%	7.68%
Auxiliary 0-1	19.25	6.11%	7.82%	5.76%
Coal 1-1	34.00	6.82%	4.97%	6.21%
Auxiliary 1-2	39.25	14.79%	15.70%	10.59%
Coal 2-2	34.00	6.82%	4.97%	6.21%
Auxiliary 2-3	39.25	14.79%	15.70%	10.59%
Coal 3-3	34.00	6.82%	4.97%	6.21%
Auxiliary 3-4	39.25	14.79%	15.70%	10.59%
Coal 4-4	34.00	6.82%	4.97%	6.21%
Auxiliary 4-5	39.25	9.31%	12.41%	10.30%
Coal 5-5	34.00	6.82%	4.97%	6.21%
Oil/Auxiliary 5-5	19.25	6.11%	7.82%	5.76%
Total Free Area		Area (D)	Area (L)	Area (P)

Area (L) = 0.75 Area (D)

Area (P) = 0.90 Area (D)

*Area percentages for the Design and LNCFS cases total to greater than 100 percent because OFA was not considered integral to windbox operation for these cases. Therefore, Area (D) and Area (L) do not have the OFA free areas weighted in and Area (P) does.

C. LNCFS Corrosion Effects

As previously mentioned, one of the main reasons for the development of the LNCFS was to minimize reducing environments along the boiler walls for corrosion control. In tangentially-fired boilers, mixing takes place in a vortex-like manner, analogous to a swirling, ascending helix. True vortex-like flow is not achieved, however. This is due to non-homogeneous vertical mixing caused by burner jet interactions, use of overfire, use of bottom auxiliary air, etc. This complex aerodynamic pattern is further complicated by the installation of the LNCFS.

As an aid to evaluating the effectiveness of the LNCFS, furnace gas was sometimes extracted from along the boiler walls (tnrough specially installed furnace gas taps) and it was analyzed for oxygen and carbon monoxide. These measurements can be an effective measure of the capabilities of the LNCFS for blanketing the boiler walls with air.

D. Gaseous Measurement Indications

In characterizing the LNCFS, attempts were made to meet two criteria: to reduce NO_x and to maintain acceptable CO levels. Basic combustion theory states that as excess oxygen levels are decreased, NO_x levels should also decrease. Eventually though, a point is reached (just before the smoke point) where CO levels will start to rise (an indication of an incipient loss in operating efficiency). Therefore, it is desired to operate at the lowest possible oxygen level, but not so low as to cause unacceptable CO levels.

In evaluating the representation of the coal combustion process in terms of NO_x and CO levels, one main difference exists. NO_x levels are indicators of average combustion conditions, whereas

CO levels may not be. As previously discussed, NO_x formation has two contributors: thermal-NO_x, which is temperature dependent, and fuel-NO_x, which is fuel-composition dependent. Considering this, NO_x concentrations seem to be fairly uniform across the flue-gas ducting. CO levels, on the other hand, are very sensitive to localized environments. In the conversion process, carbon and oxygen react to initially form CO. Then, if sufficient oxygen is present, CO will convert to CO_2. However, if there is a stratification of oxygen within the duct, then the localized areas of low oxygen will yield high CO levels.

The existence of localized high CO became apparent during the very first phases of testing because of the twelve probe gas sampling grid (see Part B). This was not unexpected because of the complex aerodynamics in multi-level-burner tangentially fired units. However, C-E, ER&E, and EPA agreed that as good operating practice, flue-gas CO levels generally should not exceed about 100 vppm. (In previous tests, the arbitrary CO limit was 200 vppm.) In most cases, localized sections of the flue gas ducts with high CO levels would also show low oxygen concentrations. However, in some cases, high CO levels were seen without corresponding low oxygen levels. This occurred when the boiler was operating under conditions which caused marginal stability (possibly due to flame flicker), with many high CO spikes. Frequently, the cause of high CO in the flue gas many have been due to a single improperly tuned burner or group of burners which operate poorly when at low excess air conditions. However, on boilers having easily tuneable burners it might be possible to operate at low excess air (for NO_x control) without producing the high CO readings (due to poor combustion) seen in some of the tests reported here. Hence all data, including those with high CO readings have been included here.

Occassionally some tests were aborted or cut short during this program due to excessively high CO readings. However, in this report, as explained in the preface, all tests (including those with high CO data or gathered at other conditions not recommended for long term operation) have been reported in order to more thoroughly document the performance of this boiler. Consequently, on most data plots throughout this report, those data points having high CO values have been tagged so that the reader may judge for him/her self how they points affect the curve shapes.

V. NOMENCLATURE

As explained above (Sections III and IV) and shown in Figure A-1, Hunter No. 2 has five elevations of tiltable burner and two elevations of overfire air (OFA) nozzles which can be tilted up or down independently of the fuel nozzles. Each burner has its own fuel air damper (FAD) which regulates the amount of secondary air that enters in the concentric ring pattern that surrounds each burner. Auxiliary air dampers control the air that enters the furnace at elevations surrounding the burner elevations. The auxiliary air nozzles tilt up and down with the burners, but, following the LNCFS modifications, they (auxiliary air) also swing from side to side (offset angles) so that the air path is not necessarily aligned with the fuel path. As explained earlier, this separation of fuel and air is the basis of the LNCFS. It serves to prolong the reaction time needed for complete combustion thus decreasing flame temperatures and NO_x formation while diverting some air along the walls to blanket the walls and protect them from flame impingement and corrosion.

In this report burner and OFA tilts are defined as zero when horizontal, positive when tilted up, and negative when down. Similarly the offset angles for the auxiliary air are defined as zero when aligned with the fuel stream and positive when deflected towards the walls.

The wall of the boiler that is closest to the stack is (by definition) the rear wall. Other walls (front, left, and right) are named as seen by an observer standing in the turbine room, and facing the boiler (with the stack on the far side of the boiler).

Generally, numbers or letters used to name boiler components run from top to bottom, north to south, west to east, and right to left as applicable. For example, the five burner elevations are labeled top to bottom 1 through 5.

For the purposes of this report, the tubes making up the furnace walls are numbered from left to right on each wall, as seen by an observer standing inside the boiler. (Note: this is opposite to C-E's convention.)

For additional information on how the boiler components are named, see the list of abbreviations, notes, and symbols at the beginning of this report.

PART B

DATA ACQUISITION AND TESTING METHODOLOGY

For the most part, boiler operating data (damper positions, fuel flow rates, etc.) were obtained from computer logs in the control room. These data included about 100 parameters to completely describe the boiler's operating mode during each test. Also, certain operating data which were not available through the computer were read locally.

In addition to extensive boiler operating data, several other types of data were gathered during the test periods including gaseous emissions (flue and furnace gases), solids testing (particulate loading and ash composition) and corrosion results. This part of the report discusses the test methods used to acquire the data reported herein.

I. GASEOUS EMISSIONS

Two different types of gas samples (flue gas and furnace gas) were analyzed (by extractive monitors). Flue gas was monitored by extractive CEM's in order to relate boiler gaseous emissions (CO, NO_x, etc.) to boiler operating mode. Furnace gas was analyzed for CO and O_2 in order to assess the wall blanketing effect of the LNCFS air offset deflector vanes for NO_x reduction and corrosion analyses.

A. Flue Gas

Figure B-1 is a simplified sketch of Hunter Unit Number 2 showing the sampling locations for the flue gas measurements. Details of the sampling system are shown in Figures B-2, B-3, and B-4.

Flue gas was sampled downstream of the boiler's economizer section and upstream of the air preheater. Hence, the sample represented combustion products rather than leaks from downstream components. At this location, the temperature of the gas being sampled was between 500 and 800°F. Sampling tubes were assembled in four probe assemblies of three probes each and inserted horizontally through ports on the sides of the two exhaust ducts (two probe assemblies in each duct). Each probe assembly consisted of a short, medium, and long tube of 3/8" stainless steel with a porous sintered stainless steel filter on the sampling end.

The twelve sampling points were located as close as possible to the centers of twelve equal and mutually exclusive co-planar areas of the ducts' cross section. The gas was analyzed as a composite sample, i.e., three points (one probe assembly) at a time. This method, though not in strict accord with EPA's Method 1, has been shown to yield a representative sample.[B1]

For each probe, the samples flowed through individual heated Teflon™ lines into a heated gas mixing/conditioning box. In the box, the three sample probe flows were combined and particulate matter was filtered from the sample while it was still hot and free of condensed moisture. Then, the sample flowed through a permeation tube dryer where water was selectively removed.

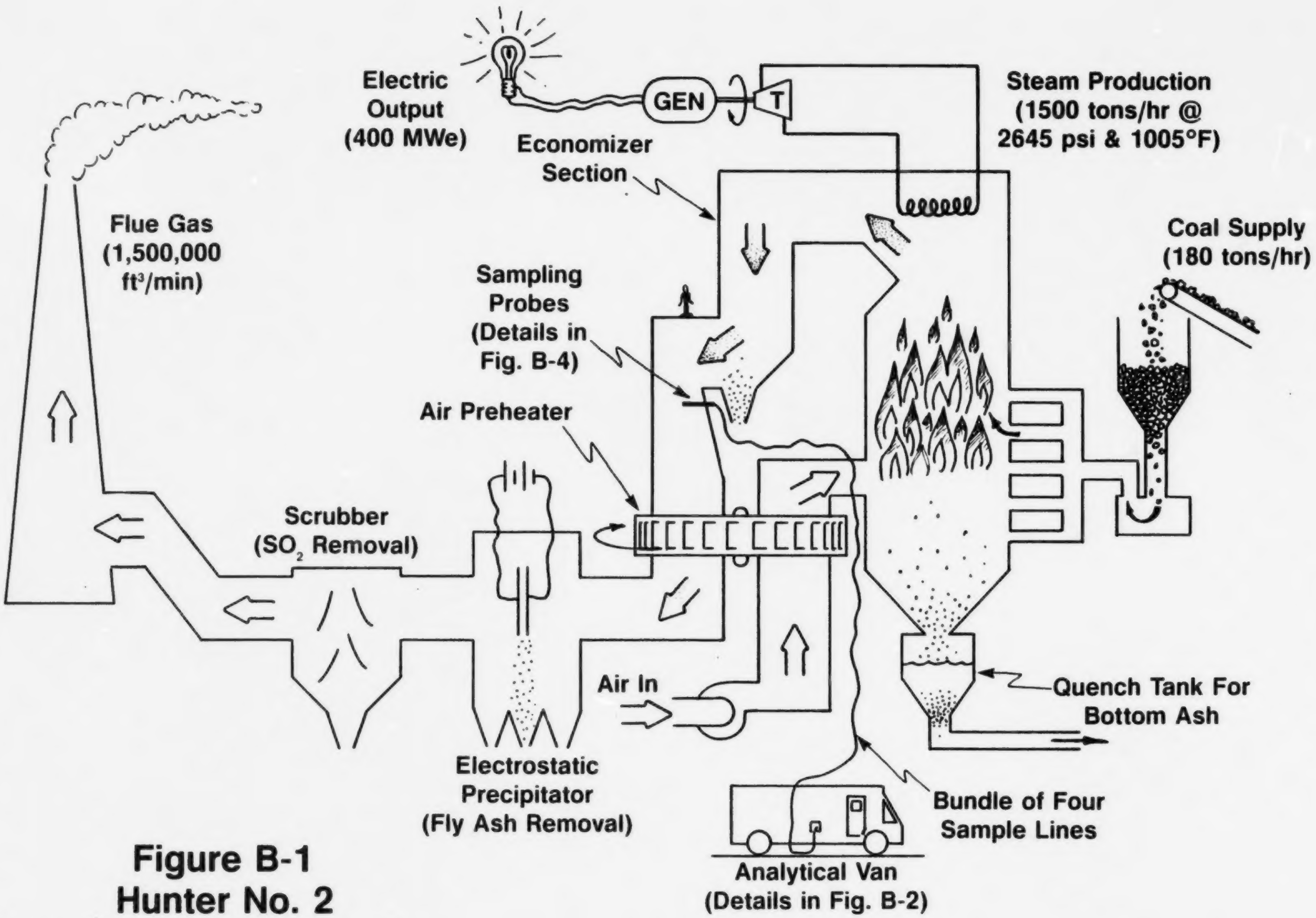

Electric
Output
(400 MWe)
GEN
T
Steam Production
(1500 tons/hr @
2645 psi & 1005°F)
Economizer
Section
Flue Gas
(1,500,000
ft³/min)
Coal Supply
(180 tons/hr)
Sampling
Probes
(Details in
Fig. B-4)
Air Preheater
Scrubber
(SO₂ Removal)
Air In
Quench Tank For
Bottom Ash
Electrostatic
Precipitator
(Fly Ash Removal)
Bundle of Four
Sample Lines
Analytical Van
(Details in Fig. B-2)

Figure B-1
Hunter No. 2
Schematic of Process Flow

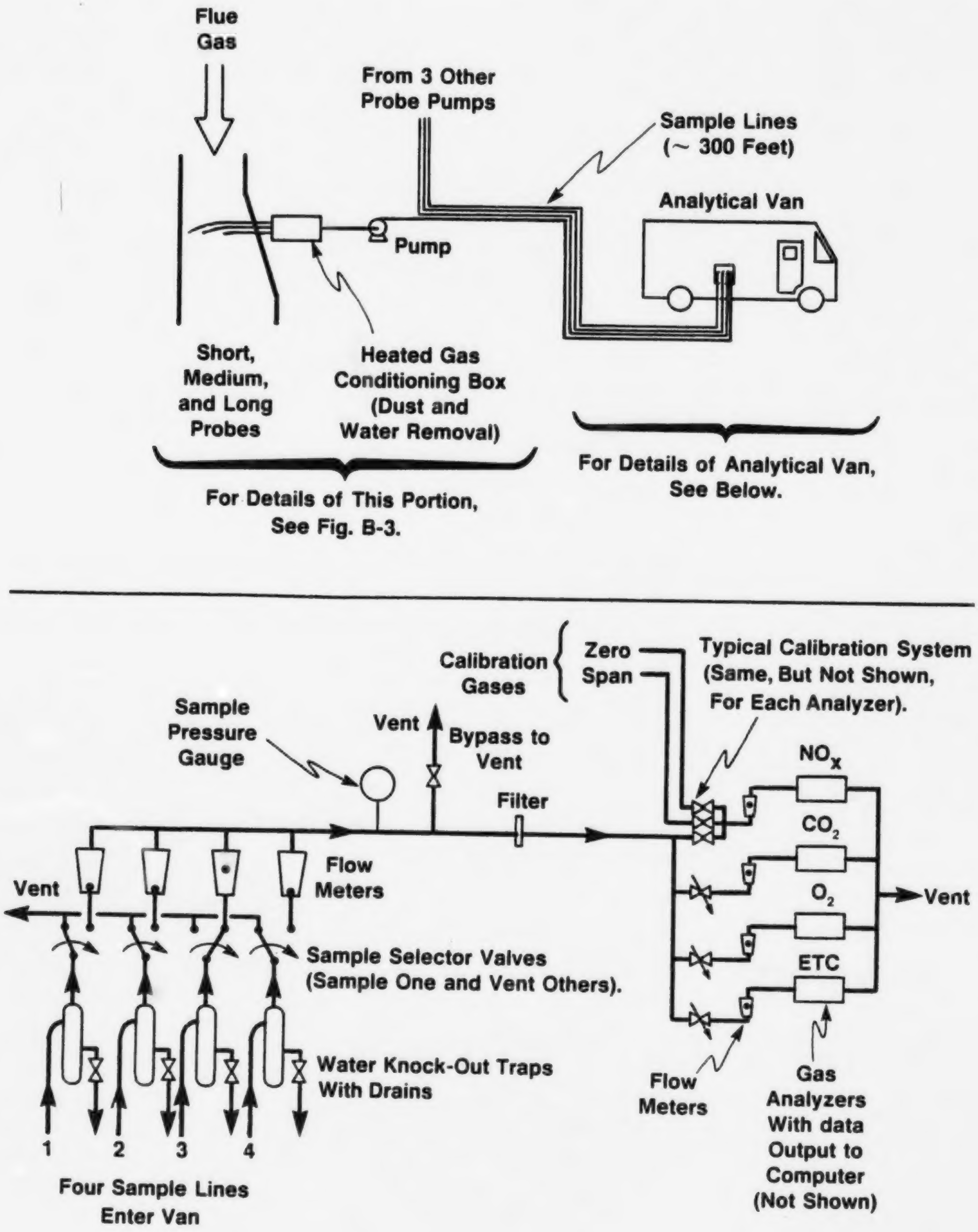

Flue Gas
From 3 Other Probe Pumps
Sample Lines (~ 300 Feet)
Analytical Van
Pump
Short, Medium, and Long Probes
Heated Gas Conditioning Box (Dust and Water Removal)
For Details of This Portion, See Fig. B-3.
For Details of Analytical Van, See Below.
Calibration Gases
Zero
Span
Typical Calibration System (Same, But Not Shown, For Each Analyzer).
Sample Pressure Gauge
Vent
Bypass to Vent
Filter
NO$_x$
CO$_2$
O$_2$
ETC
Vent
Flow Meters
Vent
Sample Selector Valves (Sample One and Vent Others).
Water Knock-Out Traps With Drains
1
2
3
4
Four Sample Lines Enter Van
Flow Meters
Gas Analyzers With data Output to Computer (Not Shown)

Figure B-2
Mobile Analytical Van

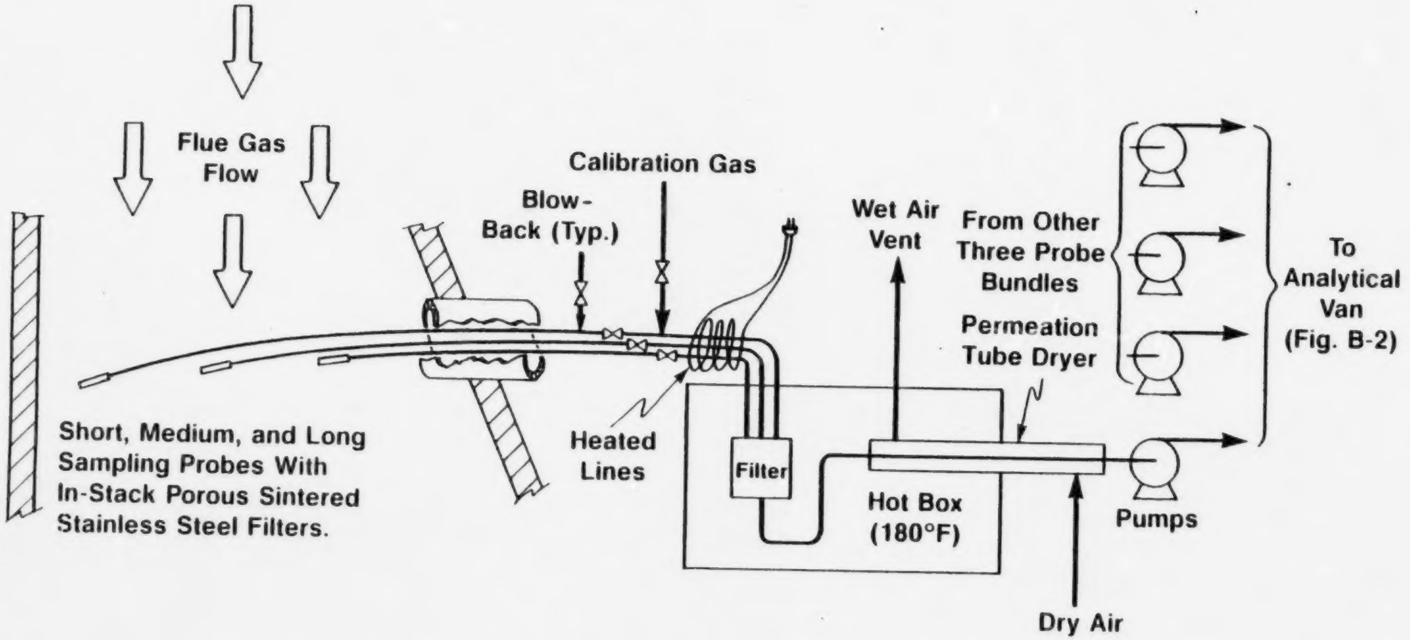
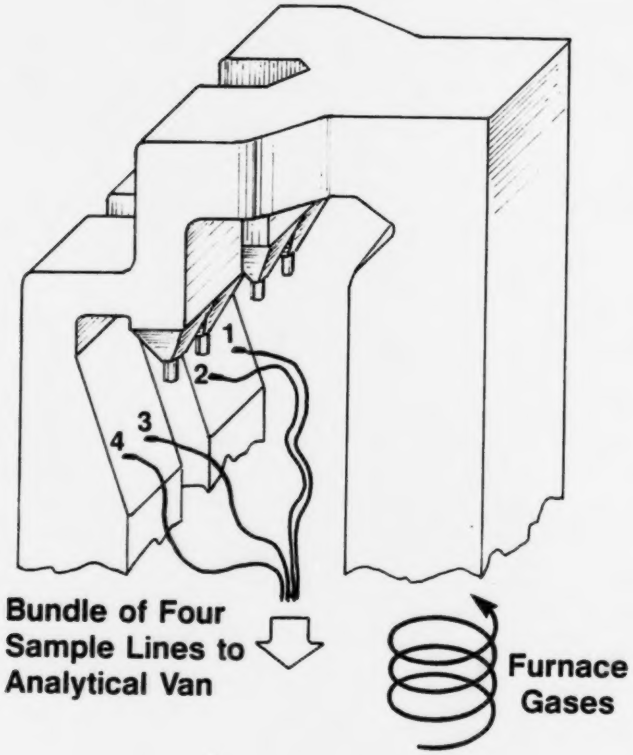

Flue Gas Flow
Calibration Gas
Blow-Back (Typ.)
Wet Air Vent
From Other Three Probe Bundles
Permeation Tube Dryer
To Analytical Van (Fig. B-2)
Short, Medium, and Long Sampling Probes With In-Stack Porous Sintered Stainless Steel Filters.
Heated Lines
Filter
Hot Box (180°F)
Pumps
Dry Air

Figure B-3
Detail of Typical Sampling Probe

1084-1-181


1
2
3
4
Bundle of Four Sample Lines to Analytical Van
Furnace Gases

(Note: Heated Gas Conditioning Boxes and Sample Pumps are Not Shown.)

For Details of Sampling Probes, See Figure B-3.

Figure B-4
Detail of Portion of Figure B-1
Showing Sampling Locations and Probe ID Numbers

Removal of dust and water vapor from the sample is important to prevent condensate sludge formation in the sample lines as they are cooled. This also prevents the loss (by absorption) of water soluble gas species while preventing freeze plugging of the sampling lines in cold weather.

With the water removed, the sample was cooled to ambient temperature as it was pumped about 300 feet (in about two minutes) to the instruments in the analytical van (Table B-1).

As the gases entered the analytical van, they passed through a final condensation (protection) trap before entering the sample selection system. The instrument operator then selected one of the four probe assembly samples to be distributed to the continuous gas analyzers. The other three probe assembly lines were continually vented, thus keeping each sample line purged with its sample flow, until ready to be analyzed. This minimized response time when switching sample lines.

Only one probe assembly (representing an equal composite from the three sampling probes), was monitored at a time. After about two minutes, the next probe assembly was sampled, and so forth.

Calibration was done by introducing a known gas composition at each gas analyzer, as well as at several probes. Leak checking was done by monitoring the sample's oxygen concentration (a leak on the vacuum side of the pump would draw in air, causing the O_2 analyzer to show an unusually high reading), and also by "dead-ending" the sampling system at various locations upstream of the running vacuum pump, while monitoring for small sample flows and pressures in the analytical van. The composition and use of the calibration gases is summarized on Table B-2.

TABLE B-1

MOBILE ANALYTICAL LABORATORY: CONTINUOUS GAS MONITORS AND CALIBRATION STANDARDS

Gas Monitored	Method	Manufacturer	Measurement Ranges	Calibration Standard*
NO/NO_x	chemiluminescent	Thermo Electron	0-2.5 ppm 0-10 ppm 0-25 ppm 0-100 ppm 0-250 ppm 0-1000 ppm 0-2500 ppm 0-10000 ppm	1 & 2
O_2	polarographic	Beckman	0-5% 0-25%	3 & 4 5
CO_2	non-dispersive infrared (NDIR)	Beckman	0-20%	3
CO	non-dispersive infrared (NDIR)	Beckman	0-500 ppm 0-1000 ppm 0-25000 ppm	3 6

* See Table B-2 for composition of calibration gas mixtures. In all cases nitrogen (mixture No. 7) was used for the "zero" check.

TABLE B-2

COMPOSITION OF STANDARD GAS MIXTURES USED FOR CALIBRATION OF GAS ANALYZERS (THIS TABLE FOR USE WITH TABLE B-1)

MIXTURE NUMBER	COMPONENTS	CONCENTRATIONS*
1	NO	477 PPM
2	NO NO_2	477 PPM 37 PPM
3	CO CO_2 CH_4 H_2 O_2 H_2O	150 PPM 13% 25 PPM 1% 4-5% Dry
4	O_2	4%, 4.8%
5	Compressed Air	100%
6	CO	165, 275, 779, 1400 and 15,000 PPM
7	N_2	100%

* Nitrogen makes up the balance of all mixes.

When evaluating boiler operating parameters, such as combustion modifications, during boiler characterization tests, the testing team would first wait for the boiler to reach steady state. Then at intervals which allowed for 30 seconds of sampling time plus sufficient purging time, the flows in each of the four sample lines would be fed, sequentially, to the gas analyzers. The cycle was repeated until each of the four sample streams had been analyzed twice (required about 20 minutes). The resulting data would be processed by the van's on line mini-computer to give a prompt hard copy (paper) report following each test. (About 6 to 8 tests could be performed in a day.) The computer report included specific probe assembly emissions plus average emissions during the test as well emissions corrected to a standard dilution of 3% oxygen (dry).

Many tests involved adjustment of the boiler's excess oxygen flow and subsequent observation of its effect on NO_x emissions. During setup for these tests, air flow was slowly decreased until CO emissions began to rise. To help monitor the boiler from its control room, a remote indicator was installed in the control room which echoed the O_2, CO, and NO_x readings displayed in the analytical van. During test setup, the instrument operator in the van switched the sample selector to monitor a location in the flue gas exhaust duct where the O_2 and CO concentrations were most critically low or high, respectively. Hence, as the boiler operator decreased the air flow rate, the operator was able to see, almost immediately, on the remote indicator, how this was affecting CO and NO_x emisisons. Observers in both the control room and the analytical van kept in constant radio contact during boiler setup. Visible stack emissions (smoke) were frequently monitored by an EPA-certified plume observer.

Each test began after a short observation period to be sure that the boiler was operating in steady state. Once in steady state, the control room observer recorded all critical boiler operating parameters so that emissions could be correlated with boiler operating mode.

The equipment used to monitor stack emissions during these tests allowed for safe boiler operation at lower excess air levels than would normally be possible with conventional boiler instrumentation. Low excess air is desirable not only for NO_x control, but also because it minimizes the amount of waste heat going up the stack as excess hot gas.

B. Gaseous Samples at Furnace Wall

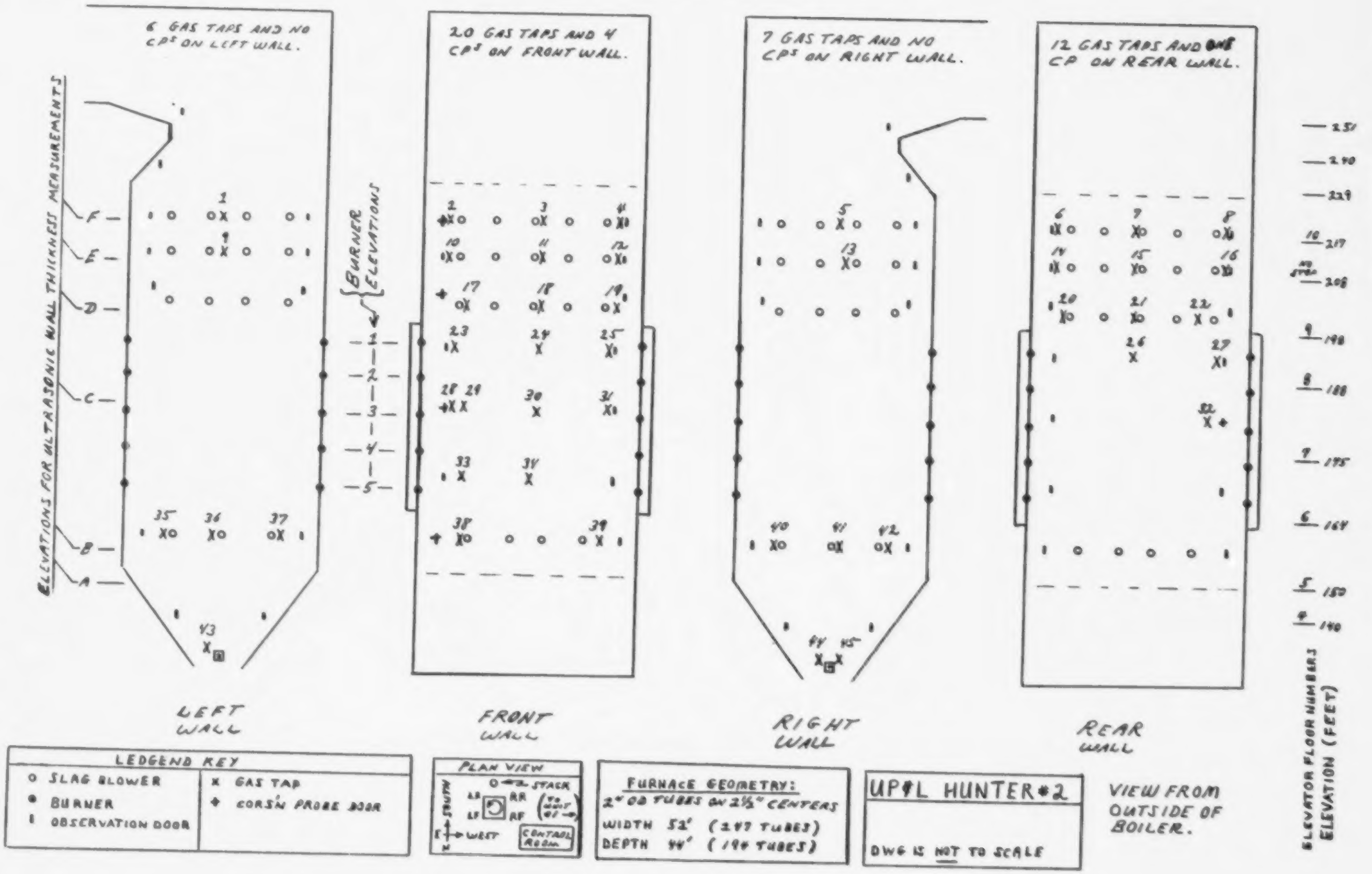
Another type of gaseous sampling (called furnace gas-tap testing) involved extracting furnace gases directly from various locations along the walls of the furnace combustion zone in order to assess the blanketing effect of the LNCFS offset angle, and to identify local potentially corrosive environments for low-NO_x and corrosion analyses.

In preparation for the furnace gas tap studies, approximately forty 1/4 inch holes were drilled through the furnace wall (in the membrane between adjacent tubes) during a boiler shutdown during installation of the LNCFS. A 1/4 inch pipe was welded over each hole so that a sample of furnace gas could be drawn through it from outside the boiler. Furnace gas tap locations are shown in Figure B-5.

During a gas tap test, furnace gas was withdrawn by a vacuum pump from the furnace (>2000°F) through a 10-20 foot length of 3/8" stainless steel tubing to cool the gas and quench the combustion reactions. This gas was analyzed on-line for O_2 and

Figure B-5 Sketch of Boiler Layout Showing Locations of:

- Gas Taps
- Corrosion Probes (highlighted in Figure B-7)
- Ultrasonic Thickness Measurements


6 GAS TAPS AND NO CPs ON LEFT WALL.
20 GAS TAPS AND 4 CPs ON FRONT WALL.
7 GAS TAPS AND NO CPs ON RIGHT WALL.
12 GAS TAPS AND ONE CP ON REAR WALL.
ELEVATIONS FOR ULTRASONIC WALL THICKNESS MEASUREMENTS
F
E
D
C
B
A
BURNER ELEVATIONS
1
2
3
4
5
LEFT WALL
FRONT WALL
RIGHT WALL
REAR WALL
— 251
— 240
— 229
10 217
NO STOP 208
9 198
8 188
7 175
6 164
5 150
4 140
ELEVATOR FLOOR NUMBERS
ELEVATION (FEET)
LEDGEND KEY
○ SLAG BLOWER
● BURNER
I OBSERVATION DOOR
x GAS TAP
✦ CORS'N PROBE DOOR
PLAN VIEW
STACK
SOUTH
WEST
LR
LF
RR
RF
(TO UNIT #1)
CONTROL ROOM
FURNACE GEOMETRY:
2" OD TUBES ON 2½" CENTERS
WIDTH 52' (247 TUBES)
DEPTH 44' (194 TUBES)
UP&L HUNTER #2
DWG IS NOT TO SCALE
VIEW FROM OUTSIDE OF BOILER.

CO concentrations. A portable MSA Model 1000 semi-continuous detector was used for analyzing oxygen concentrations as well as CO levels up to 2000 vppm. Higher CO levels were measured with a Sun Instruments Model EPA-75 analyzer. Each of these instruments is equipped with a filter/dryer for water condensation and particulate removal. The MSA instrument detects O_2 and CO concentrations using electrolytic membrane and electrochemical polarigraphic methods, respectively, while the Sun instrument determines CO levels by a non-dispersive infrared (NDIR) technique.

Each gas tap test required about two to six hours. During these tests, the boiler was maintained in a fairly steady operating mode through the use of tightly constrained boiler control. (For example, during the gas tap tests, normal soot blowing operations were suspended or curtailed, and burner tilts were fixed in place.) Also, several sets of flue gas data were taken during each gas tap test.

II. SOLID SPECIES

One of the goals of the characterization work was to assess the effects of optimized low-NO_x boiler operations on combustion efficiency and other adverse side effects.

In terms of solid species testing, combustion efficiency was evaluated (by measuring [unburned] carbon in the fly ash), while the evaluated side effects included particulate mass loadings in the flue gas and electrostatic precipitator (ESP) performance.

Fly ash samples were taken from the ESP hoppers by Exxon (ER&E) and C-E employees during specific characterization tests. Each sample was taken in a manner to ensure that the hopper sampling cylinders contained fly ash from only the specific characterization test of interest. These solid samples were then analyzed by C-E for (unburned) carbon levels.

This work assisted in optimizing the boiler's operating parameters (air flow rate, damper positions, etc.) for low-NO_x emissions without loss of combustion efficiency or other adverse side effects such as heavy particulate loading in the flue gases or loss of electrostatic precipitator (ESP) performance. (The ESP removes and controls the amount of particulate matter [fly ash] that is discharged with the flue gas into the atmosphere.)

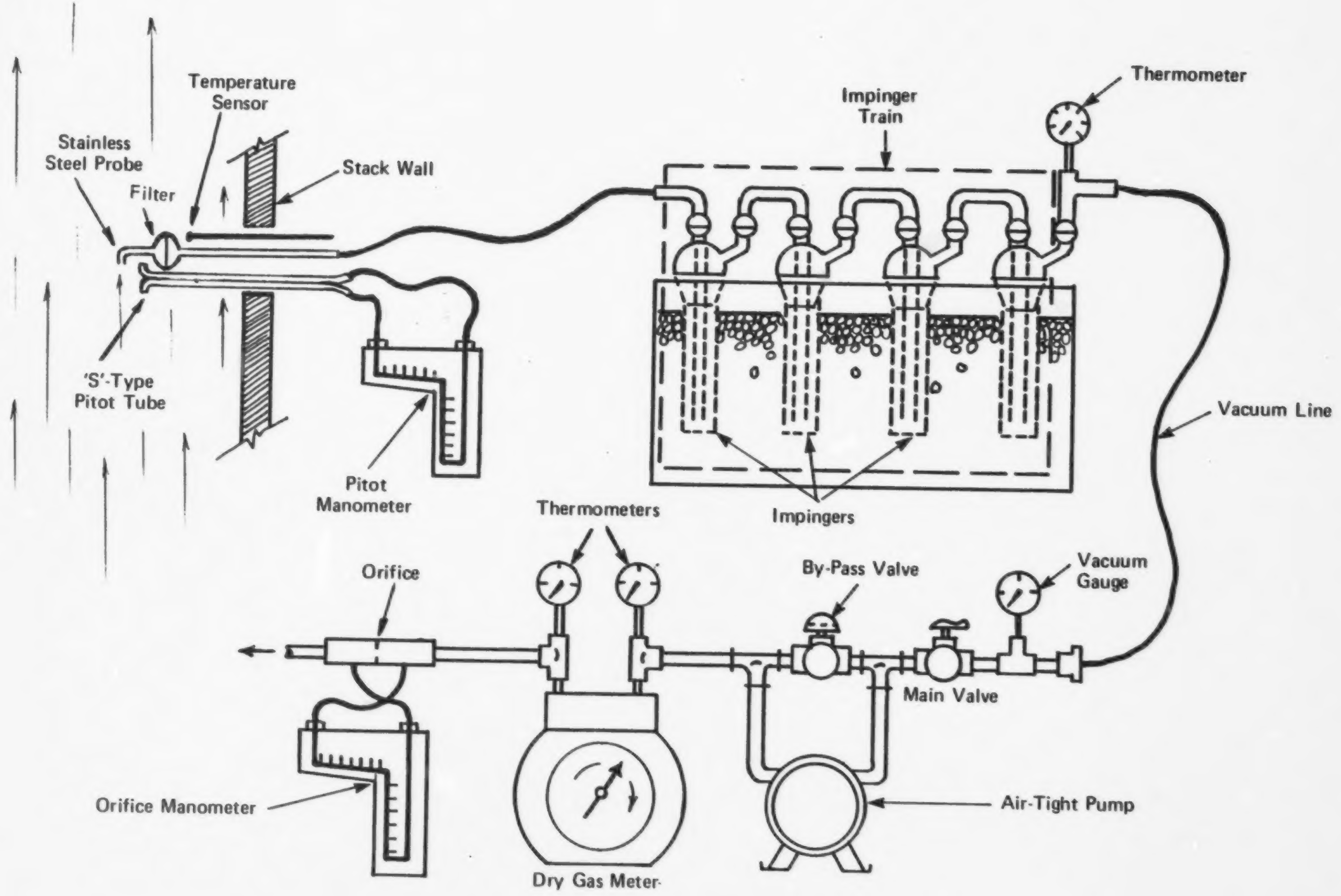
Performance of the ESP depends on the total inlet grain loading, particle size distribution, and ash resistivity. Because some of these properties could be influenced by the low-NO_x operation, an ESP performance test was conducted after the major portion of the characterization and boiler optimization work had been completed (October 1982). During the ESP performance test, ESP efficiency was determined by measuring ESP inlet and outlet grain loading in the flue gas passing through the ESP. The size distribution of those particles was also measured at the ESP inlet.

Total grain loading was determined by EPA Method 17[B2] (similar to EPA Method 5). In this method (Method 17), a measured amount of flue gas is drawn into a sampling nozzle and then through a filter which captures the entrained particulate matter. The filter is located on the sampling probe (in the duct) just behind the sampling nozzle (see Figure B-6).

The grain loading (grams per cubic meter) is determined from the weight gain of the filter (grams) divided by the amount of gas sampled (cubic meters).

Three test runs were performed over a two day period. Each run consisted of simultaneous traverses of the ESP inlet and outlet ducts

Figure B-6 EPA Method 17 Sampling System for Particulate Matter.


Temperature Sensor
Stainless Steel Probe
Filter
Stack Wall
'S'-Type Pitot Tube
Pitot Manometer
Impinger Train
Thermometer
Vacuum Line
Impingers
Thermometers
Orifice
By-Pass Valve
Vacuum Gauge
Main Valve
Orifice Manometer
Dry Gas Meter
Air-Tight Pump

(two ducts in and four out). By traversing all ducts (2 minute samples at each of about 100 points), the filter catch represented a sample that was integrated over time and distance rather than a single point in time and space.

During sampling, the gas flow rate in the duct was measured (by pitot tube) at each traverse point and the sampling rate was adjusted so that the gas velocity in the nozzle matched the velocity in the duct (isokinetic sampling). Isokinetic sampling means that the stream is being sampled without disturbing its flow, thus insuring that a representative sample is obtained.

During each test, measurements were made of gas composition, moisture content, temperature, etc. in order to calculate the gas's volumetric flow rate needed in the calculation of total particulate flow.

In addition to the total particulate loading measurements, particle size distribution (PSD) was also measured at the ESP inlet. These measurements were made using an Andersen™, size selective cascade impactor. In this device, the gas stream is sampled at a single point* in the duct (a point of average velocity) and is channeled through a series of successively smaller nozzles or jets.

The ability of the particles to follow the gas through the channeling depends on their momentum (size, mass, and velocity) and the velocity of the entraining gas. If a particle's momentum is too high for it to follow the gas around a turn, that particle will leave the gas stream and be captured on an impaction plate just behind the jet.

---

*Single point sampling eliminates the problem of changing size cutpoints (D_{50}'s) of the impactor stages that would be caused by changing the sampling rate as required to isokinetically match the spacial variation of the flue gas velocity within the duct.

The largest particles by virtue of their mass alone have high enough momentum (even at low velocities) to leave the gas stream early while the jet speed is still relatively low. Then, on each successive stage of the impactor, the jet speeds become faster and faster until even the smaller particles have enough momentum to leave the gas stream and be captured. This method effectively separates particles according to size.

III. CORROSION MONITORING

Two methods were used to monitor fireside corrosion of the boiler walls. In the corrosion probe method, pre-weighed samples of boiler wall material were inserted into the furnace (through inspection doors) for various exposure periods and their weight loss was considered to be indicative of the true corrosion rate within the furnace. The other method used was an ultrasonic method in which hundreds of points on the furnace walls were measured by a sound echo method to produce a map of furnace wall thickness throughout the boiler. Both methods are discussed in detail below.

A. Corrosion Probe Method

In the corrosion probe method, the boiler's internal (fireside) corrosion rates, were determined by measuring the weight loss of test specimens inserted into the furnace for various time periods (30 to 1000 hours). The test specimens (also called corrosion coupons or test rings) were assembled in groups of five, each of a different material. Each such assembly, together with its hardware for support, cooling, etc., was called a "corrosion probe."

At Hunter No. 2, three corrosion probe studies (tests) were performed. In the first test, five probes (each containing five coupons) were inserted into different locations within the boiler (through existing inspection doors) and exposed simultaneously to the hot furnace gases for thirty hours. In the second and third tests, the number of probes, and probe locations were the same as for the first test, but the exposure times were increased to 300 and 1000 hours, respectively. Figure B-7 shows the five exposure locations for the corrosion probes.

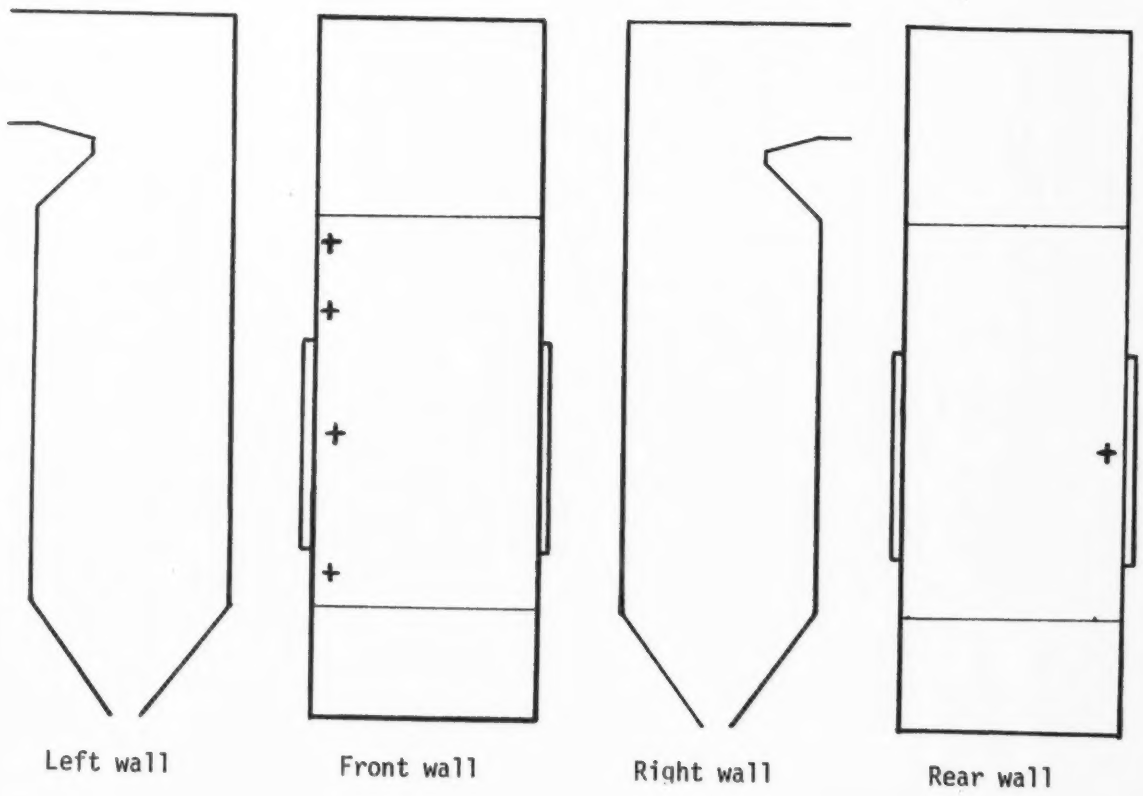
The corrosion probes (Figure B-8) and control systems were designed and built by C-E. The geometry was such that each probe could be inserted into the furnace through a standard 4" X 10" C-E inspection door. On each probe, three thermocouples (one on the center coupon, and one on each of the two end coupons) were provided for temperature measurement and control. The probes were air cooled to keep the center coupon at 650°F.

For each of the five probes in each of the three tests, a continuous log of the middle coupon's temperature was kept on a strip-chart recorder. This same data point was also used to control the probe's cooling air and high temperature alarm systems. Additionally, a data logger recorded all three thermocouple outputs from each of the five probes once per hour.

After removal from the furnace, the probes were shipped to C-E for inspection. There, slag deposits were removed and the coupon corrosion rates were determined by weight loss analysis as well as by micrometer measurements of coupon wall thicknesses.

To convert the weight loss data to a thickness change, first the weight loss (grams) for each coupon was divided by the exposed

Figure B-7 Simplified Sketch of Corrosion Probe Door Locations (see Figure B-5 for details). (View of each wall as seen from outside the boiler.)


Left wall
Front wall
Right wall
Rear wall

Key: "+" corrosion probe door (five in all)

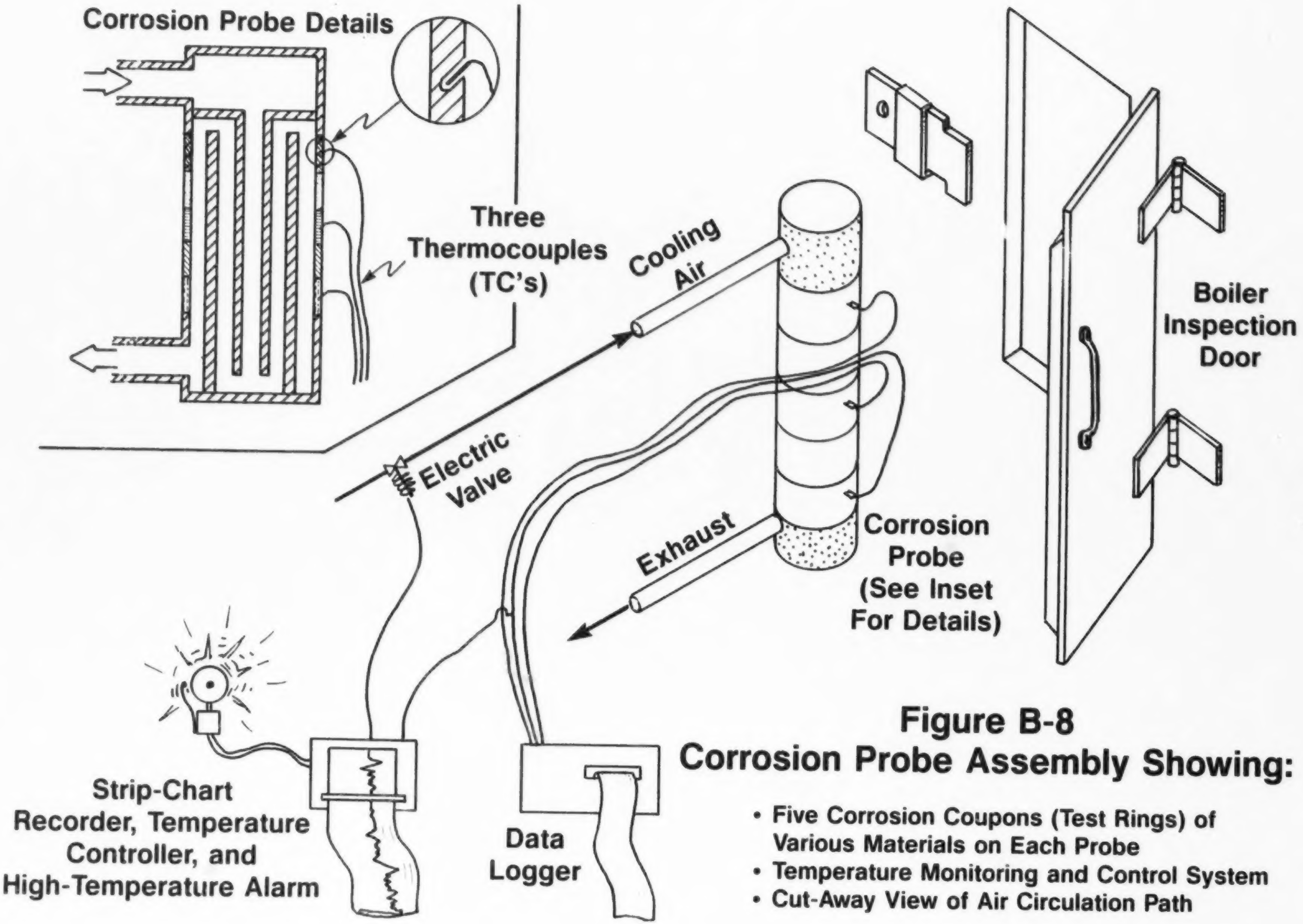

Corrosion Probe Details
Three Thermocouples (TC's)
Cooling Air
Electric Valve
Exhaust
Corrosion Probe (See Inset For Details)
Boiler Inspection Door
Strip-Chart Recorder, Temperature Controller, and High-Temperature Alarm
Data Logger

Figure B-8
Corrosion Probe Assembly Showing:

- Five Corrosion Coupons (Test Rings) of Various Materials on Each Probe
- Temperature Monitoring and Control System
- Cut-Away View of Air Circulation Path

surface area* of the coupon (cm^2) to give the weight loss per exposed surface area (g/cm^2). This number was then divided by the density of the coupon material (7.86 g/cm^3), to give the average thickness change (in centimeters) for the exposed surface. After converting to units of inches or mils (one mil = 0.001 inch) and dividing by the exposure time, the result is the average corrosion rate for the period (inches per year or mills per year).

The corrosion probe method of monitoring corrosion rates was an attractive method because it could be performed at any time since it did not require a boiler outage or a direct manned entry into the furnace. However, it did have the drawback of being an indirect measurement method. That is, when using corrosion probes, no direct measurements were made on the actual furnace walls. Instead, the corrosion rate of the furnace walls was assumed to be equal to the metal loss rate for the probes. An alternative method was to measure the furnace tube thicknesses inside the boiler directly during at least two outages as described below.

B. Ultrasonic Method of Thickness Mapping

In the ultrasonic method, tube wall thicknesses were measured directly thus producing more reliable data than the indirect data available through the corrosion probe method. However, because the ultrasonic method required a manned entry into the boiler (which could be made only during an outage) it was more expensive, more difficult, and more time consuming than the corrosion probe method.

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*For each coupon, only half of its outside surface was exposed to the radiant heat and slag in the furnace. The other half sees the furnace wall. Hence for each coupon, the exposed area is equal to half of the total visible outside surface area.

In the ultrasonic thickness (UT) method, the wall thicknesses of the furnace wall tubes were determined by echo soundings using a Krautkramer-Branson (K-B) Model CL-204 UT gauge. This K-B instrument measures the amount of time required for a high frequency sound pulse to echo off the tube's inner wall and converts the data into a four digit thickness display.

Such measurements were made at nearly 1,000 points on all four walls inside the boiler with the greatest concentration of measurements being in the burner zone and in the corners of the front and rear walls (just downstream of the burners) where corrosion was expected to be most severe because of the proximity of the flame to the wall in these areas. Measurements were made at six elevations on all four walls as shown on Figure B-5.

The first set of measurements was made during the September 1981 outage and the second (final) set was made during the outage of February 1984. The difference between the two measurements (mils) when divided by the time interval (just over two years) yields the true corrosion rate inside the furnace (mils per year).

Because the UT method transmits and receives sound waves through the tube's outer surface, careful preparation of the tube's outer surface is required to insure that the sound transmitter/receiver may be coupled to it. Tube surface preparation involved cleaning by a motorized wire brushing wheel to remove deposits until the "white" metal of the tube's outer surface was exposed. Special care was taken to ensure that all surface coatings (slag, paint, mill scale, etc.) were removed, without removing any of the tube material itself. Additionally, because some researchers feel that a freshly cleaned surface will corrode faster than an older surface, the test plan was designed to factor out any bias or change in the corrosion rate that might result from the cleaning procedure. This is explained more fully in Parts F and H of this report.

PART C

BASELINE CHARACTERIZATION TESTING

I. INTRODUCTION

The baseline characterization testing was designed to assess the effects of operational combustion modifications on NO_x emissions. To accomplish this, the boiler was tested prior to modification during typical operations, during tests designed to produce low-NO_x levels, and also during tests designed to evaluate parametric NO_x relationships. Test results were used to determine the range of acceptable boiler operating parameters for achieving reduced NO_x levels (without adversely affecting boiler operation), and also as a database for evaluating the effectiveness of windbox hardware modifications for reducing NO_x.

The boiler combustion parameters investigated were chosen based on ER&E'S AND C-E'S experience in NO_x control technology for tangential coal-fired boilers. These parameters included the following:

- Amount of excess air fired (evaluated as excess oxygen in the flue gas)

- Overfire air flow

- Fuel air flow

- Burner nozzle tilt (relative to a horizontal orientation)

- Overfire air nozzle tilt (relative to the burner nozzle tilt)

- Load

- Fuel elevations in service (for reduced loads)

In order to test these parameters, however, the boiler was required to perform outside its normal operating range. For example, the list below of boiler operating parameters compares the range evaluated with the boiler's normal set points.

Parameter	Normal Set Point	Test Range
• Excess air (as % O_2 in flue gas)	4.5%	2.3% - 7.0%
• Burner tilt (+ degrees from horizontal)	0° ±5°	-20° to +18°
• Fuel air dampers (% open)	100%	50% to 100%
• Auxiliary air dampers (% open)	~20%	0% to 37%
• Bottom auxiliary air dampers (% open)	50%	0% to 60%
• Overfire air dampers (% open)	0%	0% to 100%
• Overfire air tilt (± degrees from horizontal)	Not used	-10° to +30°

Also, as discussed in Part A, Section IV, when boiler operating conditions yielded preliminary pre-test CO levels of $\geq$ 100 vppm, these tests were discontinued and the operating conditions were modified slightly to reduce the CO levels. However, because some of the revised test conditions still placed the boiler in a region of marginal stability, there were times during a test when short-term localized high CO levels were experienced. In most cases though, these short-term localized high CO levels still translated into overall CO levels of < 100 vppm for that test.

During the first several tests, it was discovered that the automatic controls on the boiler created parametric interrelationships which made it difficult to vary (and thus evaluate) only one parameter at a time. It was not known, during testing, which additional (unintentional) changes might affect NO_x levels. Therefore, determinations of parametric relationships were reserved until after testing. This explains why there is a disproportionate amount of data for the various parameters evaluated, and also why certain analyses exhibited a moderate degree of data scatter.

II. RESULTS AND DISCUSSION

A total of 64 baseline tests were performed, with the results from 60 of these tests yielding acceptable data. These results are shown in Table C-1. The data from four of the tests were discounted due to inconsistent instrument readings.

A. Effects of Excess Oxygen, Overfire Air and Load on NO_x Levels

As discussed in Part A, Section IV, a reduction in excess air fired reduces the amount of air available in the combustion zone, and thus, should decrease the NO_x level. Test data are listed in Table C-2, and shown in Figure C-1 for different overfire air and load conditions. NO_x levels decreased approximately 50 vppm per 1% decrease in excess oxygen levels at ~400 MW_e for both overfire air and non-overfire air operation, whereas NO_x levels decreased by ~70 vppm per 1% decrease in excess O_2 levels at ~300 MW_e for both overfire air and non-overfire air operation. The difference between the 50 vppm decrease and the 70 vppm decrease may not be significant, but may be due to data scatter and/or a bias due to the fact that the 400 MW_e tests were focused in a lower excess oxygen region than the 300 MW_e tests.

According to theory, the use of overfire air diverts air from the combustion zone to just above it, thereby reducing the oxygen available in the combustion zone and simultaneously creating vertical staging. These two effects which should reduce NO_x levels, and the combined effects are demonstrated in Figures C-1 and C-2. The data used in these figures are listed

TABLE C-1 (PG 1 OF 2)
BASELINE CHARACTERIZATION TEST RESULTS
UTAH POWER AND LIGHT CO.
HUNTER GENERATING STATION, UNIT NO. 2

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
2	402	5	95	5.0	20	0	0	2	20	60	20	4.39	431	12	
3	405	5	95	4.0	0	0	0	-3	0	60	0	2.34	191	27	
4	406	5	95	4.0	0	0	0	-20	37	60	37	5.77	508	22	
5	423	5	98	4.8	0	0	0	0	25	60	25	4.41	588	35	
6	395	5	90	5.2	25	0	0	0	0	60	0	4.26	567	43	
7	406	5	85	5.0	50	0	0	0	13	0	13	4.09	519	47	
8	403	5	85	4.2	100	0	0	0	0	0	0	4.10	385	33	
9	403	5	98	5.0	12	0	0	10	20	60	20	5.21	503	44	
10	399	5	95	4.2	75	0	0	6	0	0	0	4.73	394	42	
11	399	5	95	4.0	100	0	0	7	0	0	0	4.55	375	47	
12	402	5	95	4.5	100	0	-10	6	0	0	0	4.14	374	48	
13	401	5	95	4.5	100	0	30	6	0	0	0	3.80	327	43	
14	395	5	96	5.5	0	0	0	5	21	60	21	4.70	488	62	
15	396	5	70	5.0	0	0	0	3	21	60	21	4.45	459	63	
16	394	5	50	5.1	0	0	0	7	26	60	26	4.55	387	56	
18	391	5	50	4.5	60	0	0	11	0	0	0	3.15	345	43	
19	394	5	50	5.3	60	0	0	8	18	0	18	3.99	317	49	
20	393	5	97	5.0	60	0	0	-3	0	0	0	4.16	367	37	
21	393	5	97	4.0	60	0	0	-7	0	0	0	3.21	311	46	
22	392	5	93	5.0	0	0	0	4	21	60	21	4.62	503	17	
23	394	5	93	5.0	0	0	0	-1	26	60	26	5.48	496	10	
24	390	5	93	3.7	0	0	0	2	0	60	0	2.56	355	16	
25	397	5	60	3.0	75	0	30	2	0	0	0	3.20	223	428	
27	391	5	98	5.0	25	0	0	5	18	60	18	4.57	457	13	1
28	390	5	98	5.1	100	0	0	5	5	60	5	4.55	426	12	1
29	395	5	98	4.0	100	0	0	4	0	0	0	2.24	205	15	1
30	396	5	98	4.8	25	0	0	5	21	0	21	4.29	439	12	1
31	388	5	98	5.0	25	0	0	5	20	0	20	4.42	444	12	2
33	416	5	98	5.2	0	0	0	18	29	60	29	4.88	512	13	
34	414	5	98	5.0	0	0	0	0	29	60	29	4.72	465	12	
35	415	5	98	5.0	0	0	0	-10	26	60	26	5.14	447	12	
36	415	5	98	3.5	70	0	30	-10	0	0	0	3.02	257	43	
37	411	5	98	4.7	0	0	0	0	0	60	0	3.38	382	122	
38	417	5	50	5.0	0	0	0	0	25	60	25	3.40	374	14	
39	409	5	98	5.0	100	0	0	0	22	0	22	4.38	403	11	2,3
40	413	5	98	5.0	0	0	0	0	29	60	29	4.82	457	13	
41	411	5	98	5.0	0	0	0	0	20	60	20	3.41	418	14	
42	412	5	98	4.0	100	0	0	0	0	0	0	2.06	302	42	1,3
43	413	5	98	5.0	25	0	0	0	23	0	23	4.26	410	25	3
44	415	5	98	5.0	50	0	0	0	20	0	20	4.10	388	25	3
45	411	5	98	5.0	100	0	0	0	8	0	8	4.01	360	11	3

TABLE C-1 (PG 2 OF 2)
BASELINE CHARACTERIZATION TEST RESULTS
UTAH POWER AND LIGHT CO.
HUNTER GENERATING STATION, UNIT NO. 2

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
46	391	5	98	5.0	100	0	0	0	0	60	0	5.56	450	11	
47	391	5	98	5.0	100	0	0	0	18	0	18	5.53	430	14	
48	385	5	98	4.5	100	0	0	0	0	0	0	4.39	360	16	
49	389	5	98	4.5	100	0	30	0	0	0	0	3.97	323	18	
50	391	5	50	4.5	100	0	30	0	0	0	0	3.83	294	18	
51	395	5	50	5.2	0	0	0	0	29	0	29	4.39	396	15	
52	307	4	80	4.7	0	0	0	16	0	60	0	5.56	456	14	4
53	299	4	80	3.5	0	0	0	11	0	60	0	4.20	361	11	4
54	302	4	80	5.0	0	0	0	10	5	60	5	7.00	528	20	4
55	300	4	80	3.5	45	0	0	10	0	60	0	6.55	392	14	4
56	300	4	80	3.8	60	0	0	10	0	0	0	6.39	364	14	4
57	301	4	80	3.3	40	0	0	10	0	0	0	5.80	339	16	4
58	297	4	80	3.5	40	0	30	10	0	0	0	5.23	327	13	4
59	300	5	85	2.7	0	0	0	0	0	60	0	5.13	489	15	
60	302	4	100	4.0	0	0	0	0	0	60	0	5.51	506	14	5
61	301	4	100	3.2	0	0	0	0	0	60	0	4.13	416	20	5
62	299	4	100	4.8	0	0	0	0	8	60	8	6.62	596	13	5
63	302	4	100	4.0	60	0	0	0	0	0	0	6.40	469	10	5
64	297	4	100	3.6	40	0	0	0	0	0	0	5.47	402	12	5

NOTES:
1. LOWER LEVEL OF OVERFIRE AIR COMPARTMENTS CLOSED.
2. UPPER LEVEL OF OVERFIRE AIR COMPARTMENTS CLOSED.
3. LEFT FRONT OVERFIRE AIR COMPARTMENT AT +10 DEGREE TILT.
4. LOWER FOUR COAL ELEVATIONS USED.
5. UPPER FOUR COAL ELEVATIONS USED.

ABBREVIATIONS (For Computerized Tables in Parts C and D of This Report)

AUX BANK:	The bank of auxiliary air compartment damper settings (% open).
AUX 4-5:	Oil gun auxiliary air compartment damper settings (% open).
AUX 5:	Bottom auxiliary air compartment damper settings (% open).
Burner Tilt:	Fuel (burner) nozzle tilts, in degrees relative to the horizontal. (Up is positive.)
CO VPPM:	Flue gas carbon monoxide levels in VPPM, corrected to 3 volume percent oxygen on a dry basis.
DELTA P:	Windbox/furnace pressure differential, measured in inches of water.
ELEV:	Number of fuel elevations in service.
FAD:	Fuel air damper settings (% open).
MWE:	Electricity generated, in megawatts (gross)
NO_x VPPM:	Flue gas oxides of nitrogen levels in vppm, corrected to 3 volume percent oxygen on a dry basis.
OFAD:	Overfire air compartment damper settings (% open).
OFAT:	Overfire air nozzle tilts, in degrees relative to the horizontal. (Up is positive.)
OFFSET:	Angle differential between the fuel nozzles and the auxiliary air compartments.
PERCENT 02:	Volume percentage of excess oxygen in the (dry) flue gas.

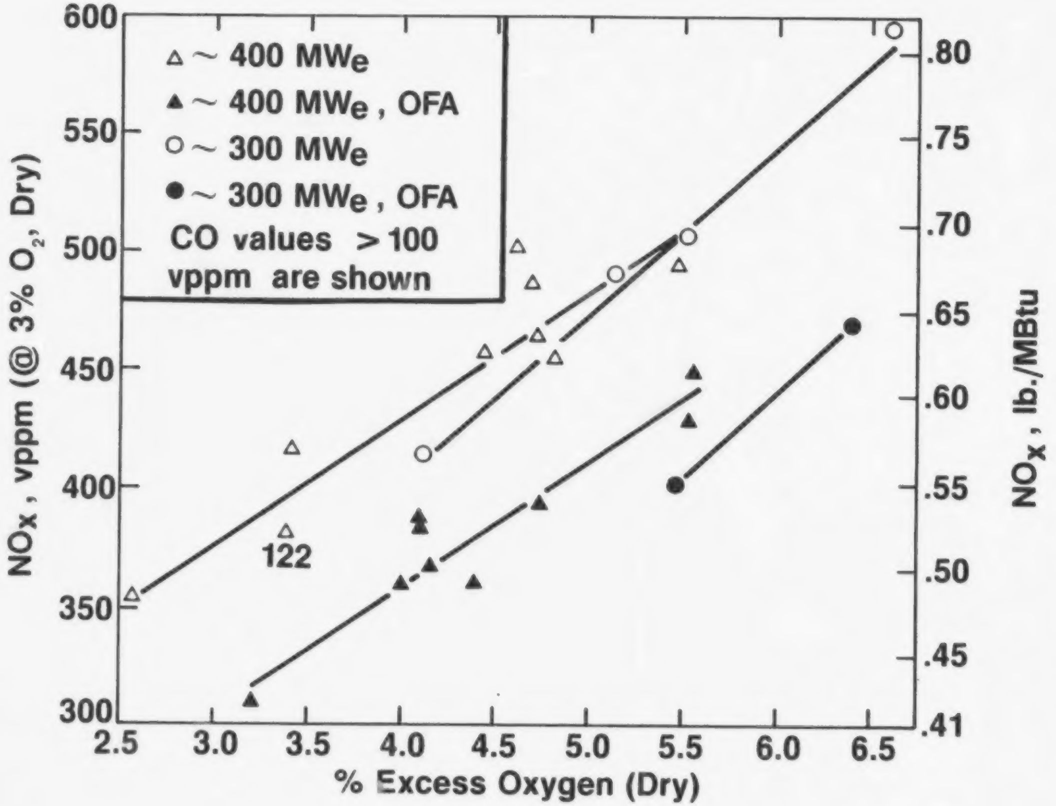

Figure C-1
Effects of Excess Oxygen, Overfire Air and Load on NO_x Levels

TABLE C-2
BASELINE CHARACTERIZATION TESTS
EFFECTS OF EXCESS OXYGEN, OVERFIRE AIR AND LOAD ON NOX LEVELS

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM
~ 400 MWE														
14	395	5	96	5.5	0	0	0	5	21	60	21	4.70	488	62
15	396	5	70	5.0	0	0	0	3	21	60	21	4.45	459	63
22	392	5	93	5.0	0	0	0	4	21	60	21	4.62	503	17
23	394	5	93	5.0	0	0	0	-1	26	60	26	5.48	496	10
24	390	5	93	3.7	0	0	0	2	0	60	0	2.56	355	16
34	414	5	98	5.0	0	0	0	0	29	60	29	4.72	465	12
37	411	5	98	4.7	0	0	0	0	0	60	0	3.38	382	122
40	413	5	98	5.0	0	0	0	0	29	60	29	4.82	457	13
41	411	5	98	5.0	0	0	0	0	20	60	20	3.41	418	14
~400 MWE, OFA														
8	403	5	85	4.2	100	0	0	0	0	0	0	4.10	385	33
10	399	5	95	4.2	75	0	0	6	0	0	0	4.73	394	42
20	393	5	97	5.0	60	0	0	-3	0	0	0	4.16	367	37
21	393	5	97	4.0	60	0	0	-7	0	0	0	3.21	311	46
44	415	5	98	5.0	50	0	0	0	20	0	20	4.10	388	25
45	411	5	98	5.0	100	0	0	0	8	0	8	4.01	360	11
46	391	5	98	5.0	100	0	0	0	0	60	0	5.56	450	11
47	391	5	98	5.0	100	0	0	0	18	0	18	5.53	430	14
48	385	5	98	4.5	100	0	0	0	0	0	0	4.39	360	16
~300 MWE														
59	300	5	85	2.7	0	0	0	0	0	60	0	5.13	489	15
60	302	4	100	4.0	0	0	0	0	0	60	0	5.51	506	14
61	301	4	100	3.2	0	0	0	0	0	60	0	4.13	416	20
62	299	4	100	4.8	0	0	0	0	8	60	8	6.62	596	13
~300 MWE, OFA														
63	302	4	100	4.0	60	0	0	0	0	0	0	6.40	469	10
64	297	4	100	3.6	40	0	0	0	0	0	0	5.47	402	12

CONDITIONS:
FAD $\geqslant$ 70% OPEN;
BTILT = $0^\circ \pm 7^\circ$;
DATA USED IN FIGURE C-1.

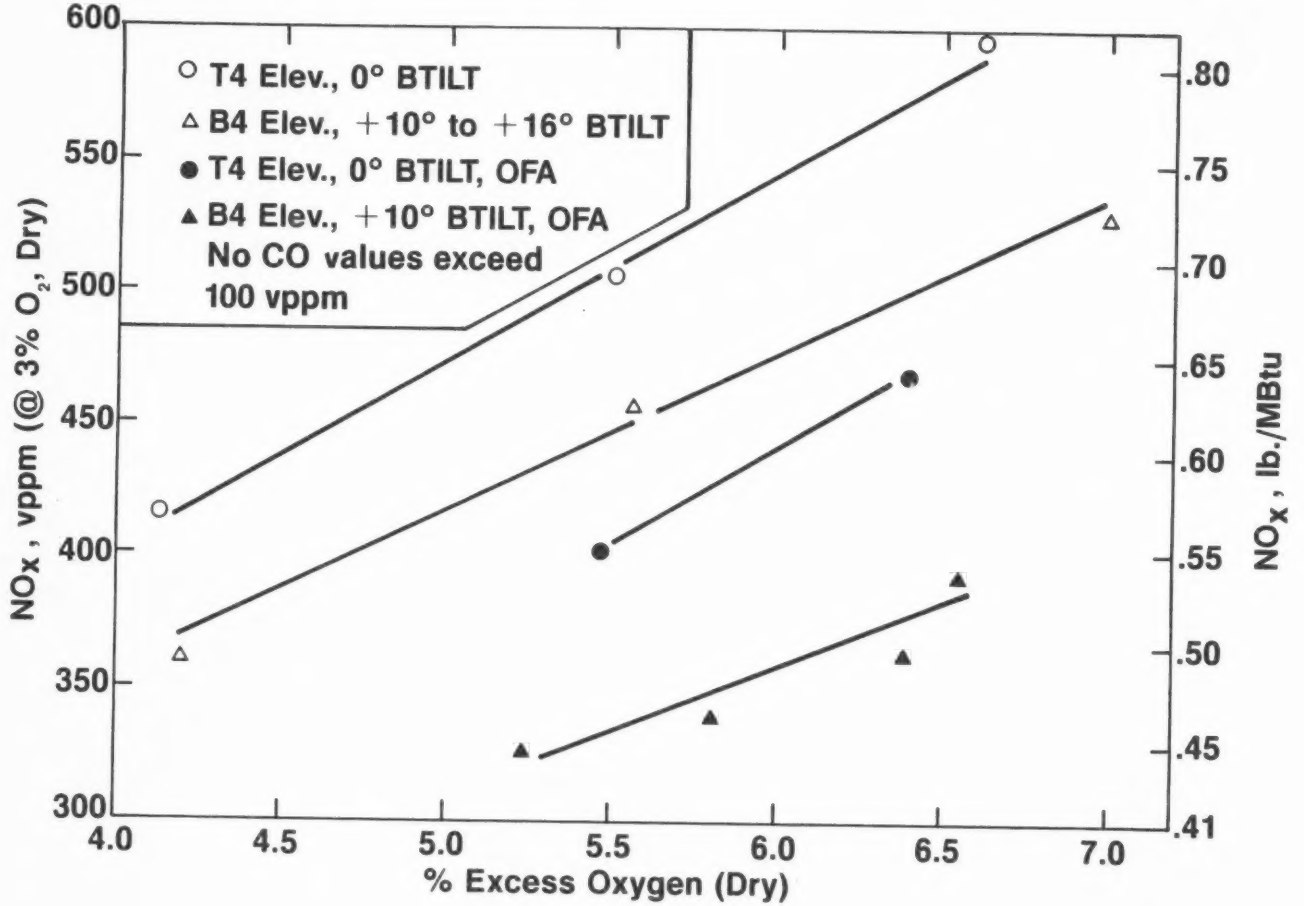

Figure C-2
Effects of Overfire Air, and Fuel Elevations on NO_x at ~ 300 MWe Load

TABLE C-3
BASELINE CHARACTERIZATION TESTS
EFFECTS OF OVERFIRE AIR AND FUEL ELEVATIONS ON NOX AT ~300 MWE LOAD

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM
TOP 4 ELEVATIONS														
60	302	4	100	4.0	0	0	0	0	0	60	0	5.51	506	14
61	301	4	100	3.2	0	0	0	0	0	60	0	4.13	416	20
62	299	4	100	4.8	0	0	0	0	8	60	8	6.62	596	13
BOTTOM 4 ELEVATIONS														
52	307	4	80	4.7	0	0	0	16	0	60	0	5.56	456	14
53	299	4	80	3.5	0	0	0	11	0	60	0	4.20	361	11
54	302	4	80	5.0	0	0	0	10	5	60	5	7.00	528	20
TOP 4 ELEVATIONS, OVERFIRE AIR														
63	302	4	100	4.0	60	0	0	0	0	0	0	6.40	469	10
64	297	4	100	3.6	40	0	0	0	0	0	0	5.47	402	12
BOTTOM 4 ELEVATIONS, OVERFIRE AIR														
55	300	4	80	3.5	45	0	0	10	0	60	0	6.55	392	14
56	300	4	80	3.8	60	0	0	10	0	0	0	6.39	364	14
57	301	4	80	3.3	40	0	0	10	0	0	0	5.80	339	16
58	297	4	80	3.5	40	0	30	10	0	0	0	5.23	327	13

CONDITIONS:
FAD ≥ 80% OPEN;
ONLY 4 FUEL ELEVATION TEST RESULTS;
DATA USED IN FIGURE C-2.

in Tables C-2 and C-3, respectively. In Figure C-1, the use of overfire air decreased NO_x levels by ~75 vppm at 400 MW_e. For normal 300 MW_e operations, i.e., with the top 4 fuel elevations in service, overfire air usage yielded a decrease in NO_x levels of ~105 ppm, as shown in Figure C-2. Also, for 300 MW_e operation with the bottom four fuel elevations in service (shown in Figure C-2), overfire air usage reduced NO_x levels by ~115 vppm. The greater reductions in NO_x levels with overfire air at 300 MW_e compared to 400 MW_e can be attributed to a greater degree of staging that naturally occurs at lower loads when using overfire air.

The level of overfire air used determines the degree of vertical staging, which subsequently impacts on NO_x reductions. This effect of overfire air levels on NO_x emissions is shown in Figure C-3, with the test data listed in Table C-4. In this analysis, overfire air flow rates have been grouped into three categories: low overfire air flow (where one or two elevations of overfire air dampers were open $\leq$ 25%), medium overfire air flow (where either one elevation of overfire air dampers was 100% open or two elevations were 50% open), and high overfire air flow (where both overfire elevations were open $\geq$ 60%). From the figure (C-3), it is shown that low level overfire air decreased NO_x levels by a modest amount, (i.e., <20 ppm) while medium and high levels of overfire air decreased NO_x levels by approximately 45 vppm and 75 vppm, respectively.

Regarding the effect of load on NO_x levels, all of the baseline characterization tests were performed at either 75% load or full load. This was because testing emphasis was initially placed on reducing NO_x emission rates, which are greatest at the higher loads. Therefore, the only load effects evaluated were comparisons of NO_x levels at 300 and 400 MW_e, both with and without overfire air. The data used in evaluating these

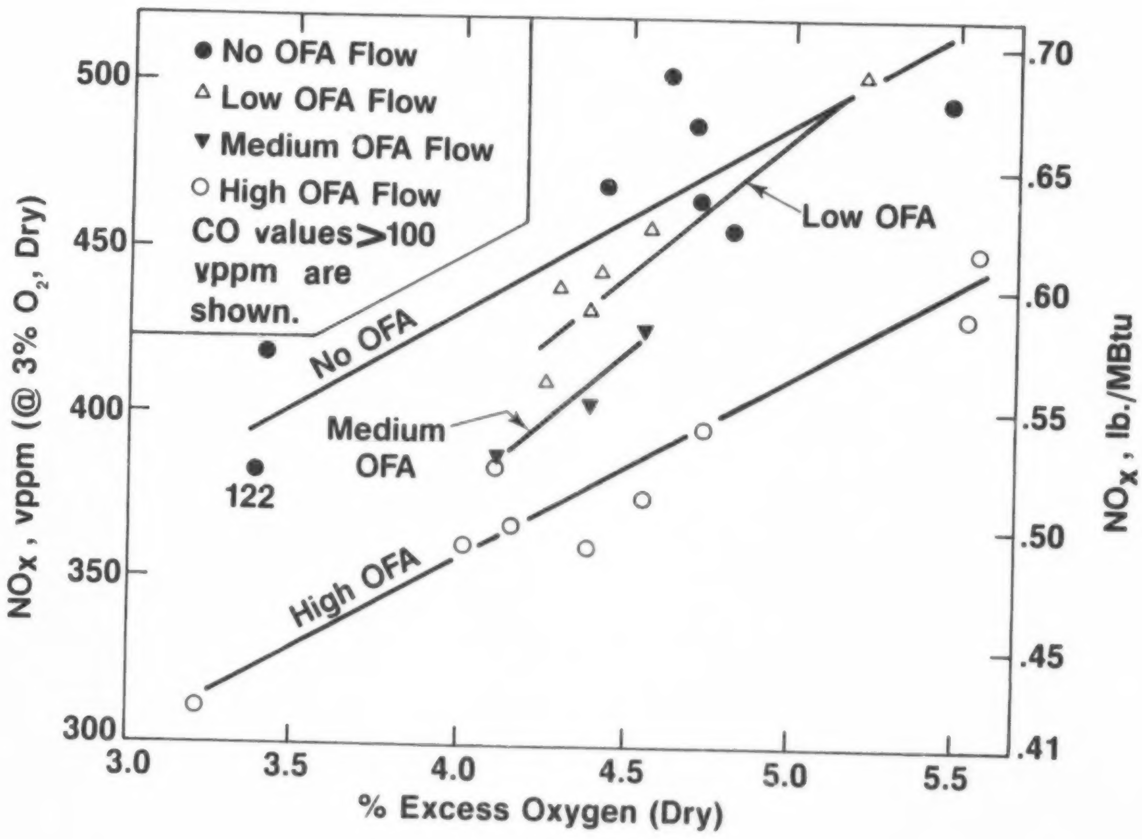

Figure C-3
Effect of Overfire Air Levels on NO_x Emissions at Full Load

TABLE C-4
BASELINE CHARACTERIZATION TESTS
EFFECTS OF OVERFIRE AIR LEVELS ON NOX EMISSIONS AT FULL LOAD

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	SINGLE OFA ELEVATION
NO OVERFIRE AIR															
14	395	5	96	5.5	0	0	0	5	21	60	21	4.70	488	62	
15	396	5	70	5.0	0	0	0	3	21	60	21	4.45	459	63	
22	392	5	93	5.0	0	0	0	4	21	60	21	4.62	503	17	
23	394	5	93	5.0	0	0	0	-1	26	60	26	5.48	496	10	
34	414	5	98	5.0	0	0	0	0	29	60	29	4.72	465	12	
37	411	5	98	4.7	0	0	0	0	0	60	0	3.38	382	122	
40	413	5	98	5.0	0	0	0	0	29	60	29	4.82	457	13	
41	411	5	98	5.0	0	0	0	0	20	60	20	3.41	418	14	
LOW OVERFIRE AIR FLOW															
2	402	5	95	5.0	20	0	0	2	20	60	20	4.39	431	12	
9	403	5	98	5.0	12	0	0	10	20	60	20	5.21	503	44	
27	391	5	98	5.0	25	0	0	5	18	60	18	4.57	457	13	X
30	396	5	98	4.8	25	0	0	5	21	0	21	4.29	439	12	X
31	388	5	98	5.0	25	0	0	5	20	0	20	4.42	444	12	X
43	413	5	98	5.0	25	0	0	0	23	0	23	4.26	410	25	
MEDIUM OVERFIRE AIR FLOW															
28	390	5	98	5.1	100	0	0	5	5	60	5	4.55	426	12	X
39	409	5	98	5.0	100	0	0	0	22	0	22	4.38	403	11	X
44	415	5	98	5.0	50	0	0	0	20	0	20	4.10	388	25	
HIGH OVERFIRE AIR FLOW															
8	403	5	85	4.2	100	0	0	0	0	0	0	4.10	385	33	
10	399	5	95	4.2	75	0	0	6	0	0	0	4.73	394	42	
11	399	5	95	4.0	100	0	0	7	0	0	0	4.55	375	47	
20	393	5	97	5.0	60	0	0	-3	0	0	0	4.16	367	37	
21	393	5	97	4.0	60	0	0	-7	0	0	0	3.21	311	46	
45	411	5	98	5.0	100	0	0	0	8	0	8	4.01	360	11	
46	391	5	98	5.0	100	0	0	0	0	60	0	5.56	450	11	
47	391	5	98	5.0	100	0	0	0	18	0	18	5.53	430	14	
48	385	5	98	4.5	100	0	0	0	0	0	0	4.39	360	16	

CONDITIONS:
FAD ≥ 70 % OPEN;
BTILT - 0 ± 10 ;
DATA USED IN FIGURE C-3.

effects are listed in Table C-2, and shown in Figure C-1. For non-overfire air operation, the difference in NO_x levels between 300 and 400 MW_e operations was minimal (i.e., <15 vppm). With overfire air, however, 300 MW_e operation yielded lower NO_x levels by about 30 vppm, though this is based on limited 300 MW_e data. Such a difference could be traced to a greater degree of vertical staging plus lower thermal NO_x at the lower load.

B. Effects of Burner Tilt and Overfire Air Compartment Tilt on NO_x Levels

The effect of burner tilt on NO_x emissions at full load, for non-overfire air operation is shown in Figure C-4, with the test data listed in Table C-5. On the average, there was a 25 vppm decrease in NO_x levels for a 10° decrease in burner tilt. According to the boiler manufacturer (C-E), this trend is unit dependent. Some tangentially-fired units show the opposite trend; that is an increase in NO_x levels when burners are tilted down.

In overfire air operation, because the degree of vertical staging greatly affects NO_x levels, burner tilt must be viewed in conjunction with overfire air tilt. For comparable overfire air levels, one would expect the degree of staging (and subsequent NO_x reduction) to increase with increasing differential angle between the overfire air and burner nozzle tilts. This theory was evaluated in tests listed in Table C-6 and shown in Figure C-5. In the figure, angle differentials (i.e., overfire air compartment angle minus the burner tilt angle) have been shown next to the data points. Based on this figure, a large increase in differential angle (e.g., an increase of $\geq 30°$) was required to reduce NO_x levels by a slight amount (i.e., a

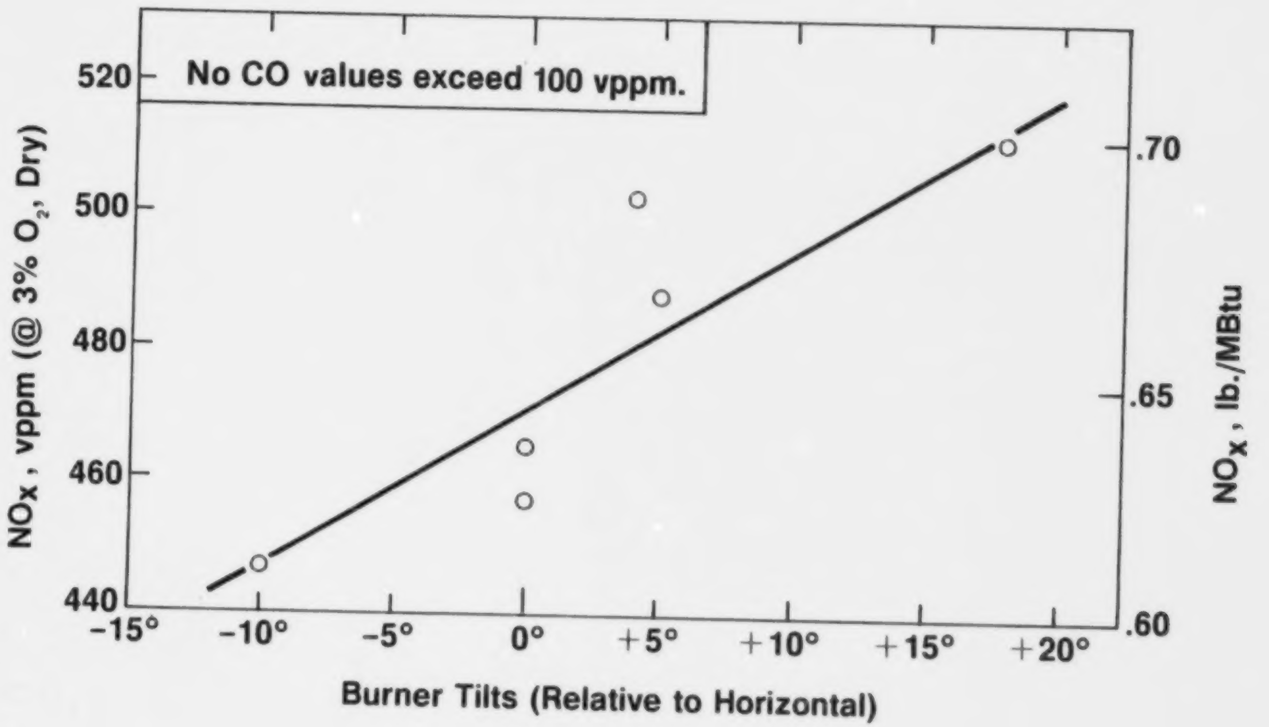

Figure C-4
Effect of Burner Tilt on NO_X at Full Load

TABLE C-5
BASELINE CHARACTERIZATION TESTS
EFFECT OF BURNER TILT ON NOX

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT 02	NOX VPPM	CO VPPM
14	395	5	96	5.5	0	0	0	5	21	60	21	4.70	488	62
22	392	5	93	5.0	0	0	0	4	21	60	21	4.62	503	17
33	416	5	98	5.2	0	0	0	18	29	60	29	4.88	512	13
34	414	5	98	5.0	0	0	0	0	29	60	29	4.72	465	12
35	415	5	98	5.0	0	0	0	-10	26	60	26	5.14	447	12
40	413	5	98	5.0	0	0	0	0	29	60	29	4.82	457	13

CONDITIONS:
LOAD = 400 MWE;
FAD ⩾ 93% OPEN;
NO OFA;
5 ELEVATIONS;
DATA USED IN FIGURE C-4.

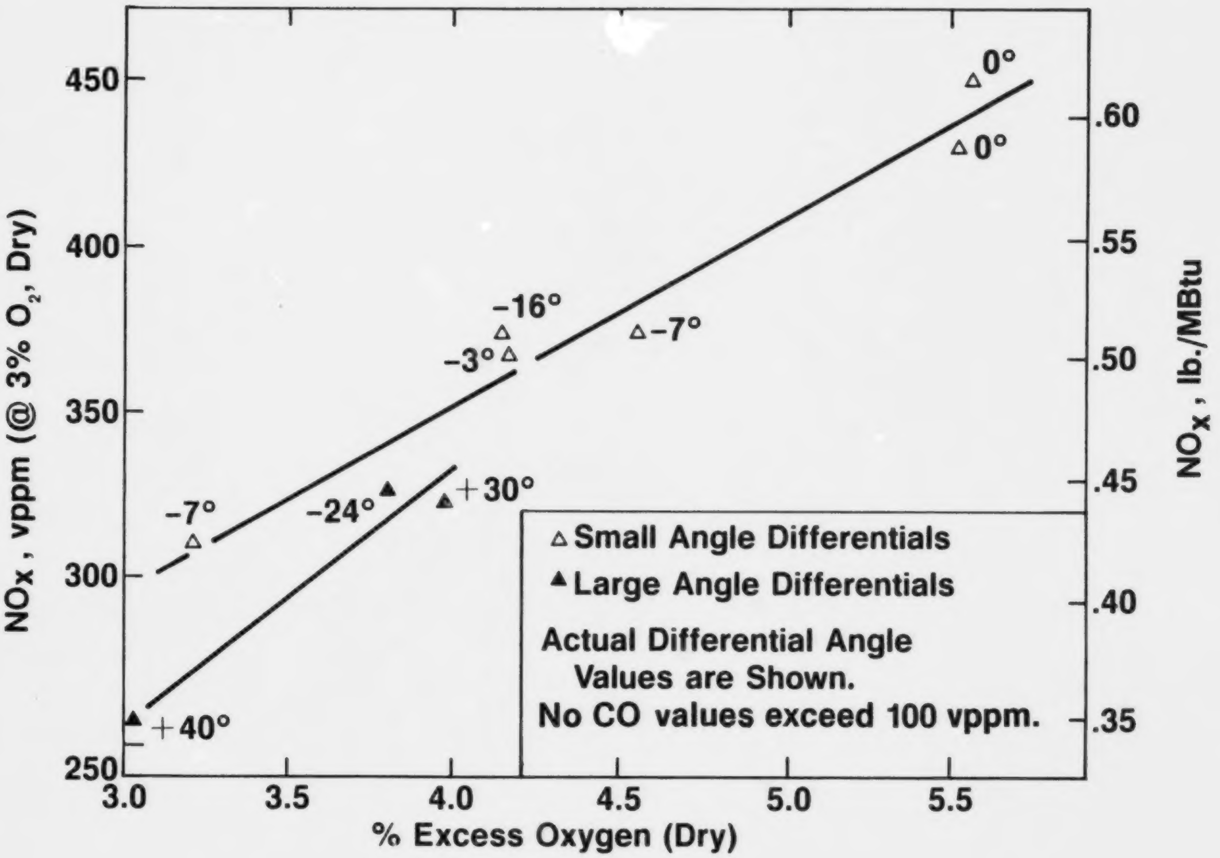

Figure C-5
Effect of Angle Differential (Overfire Air Tilt–Burner Tilt) on NO_x Levels at Full Load

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TABLE C-6
BASELINE CHARACTERIZATION TESTS
EFFECTS OF ANGLE DIFFERENTIAL (OVERFIRE AIR TILT - BURNER TILT) ON NOX LEVELS

SMALL ANGLE DIFFERENTIAL

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM
11	399	5	95	4.0	100	0	0	7	0	0	0	4.55	375	47
12	402	5	95	4.5	100	0	-10	6	0	0	0	4.14	374	48
20	393	5	97	5.0	60	0	0	-3	0	0	0	4.16	367	37
21	393	5	97	4.0	60	0	0	-7	0	0	0	3.21	311	46
46	391	5	98	5.0	100	0	0	0	0	60	0	5.56	450	11
47	391	5	98	5.0	100	0	0	0	18	0	18	5.53	430	14
LARGE ANGLE DIFFERENTIAL														
13	401	5	95	4.5	100	0	30	6	0	0	0	3.80	327	43
36	415	5	98	3.5	70	0	30	-10	0	0	0	3.02	257	43
49	389	5	98	4.5	100	0	30	0	0	0	0	3.97	323	18

CONDITIONS:
LOAD = ~400 MWE;
5 FUEL ELEVATIONS IN SERVICE;
FAD ≥ 95% OPEN;
DATA USED IN FIGURE C-5.

reduction of $\leq$ 30 vppm). Thus, the effect of differential angle on NO_x levels was not as dramatic as anticipated.

C. Effect of Fuel Air Damper Position on NO_x Levels

The effect of fuel air damper position on NO_x for full load, non-overfire air operation is shown in Figure C-6, with the test data listed in Table C-7. A reduction in the fuel air damper setting from fully open to 50% open decreased NO_x levels by an average of ~50 vppm. This reduction can be traced to a diversion of some of the fuel air from the ring surrounding each burner to the auxiliary air compartments (between burners). This diversion of air reduces the oxygen concentration at the point of ignition, and also moves the flame front closer to the coal nozzles. Both of these effects increase the degree of three dimensional boiler staging.

D. Effect of Fuel Elevations In Service on NO_x Levels

In coal-fired boilers, significant reductions in load are obtained by removing fuel elevations (mills) from service. At the Hunter No. 2 Unit, when shedding load, five mill operation is utilized from full load down to about 300 ±20 MW_e, before four mill operation takes over. Four mill operation is then used down to about 200 ±20 MW_e before three mill operation takes over. Usually, at Hunter No. 2, when in four-mill operation, the mills supplying the top four fuel elevations are used, unless one of these mills is down for repair.

Tests were performed at ~300 MW_e to evaluate the effect of fuel elevations in service on NO_x emissions. These results are shown in Figure C-2 and listed in Table C-3. For convenience, tests using the bottom four (B4) and top four (T4) elevations have been identified in the text as well as in the figure using

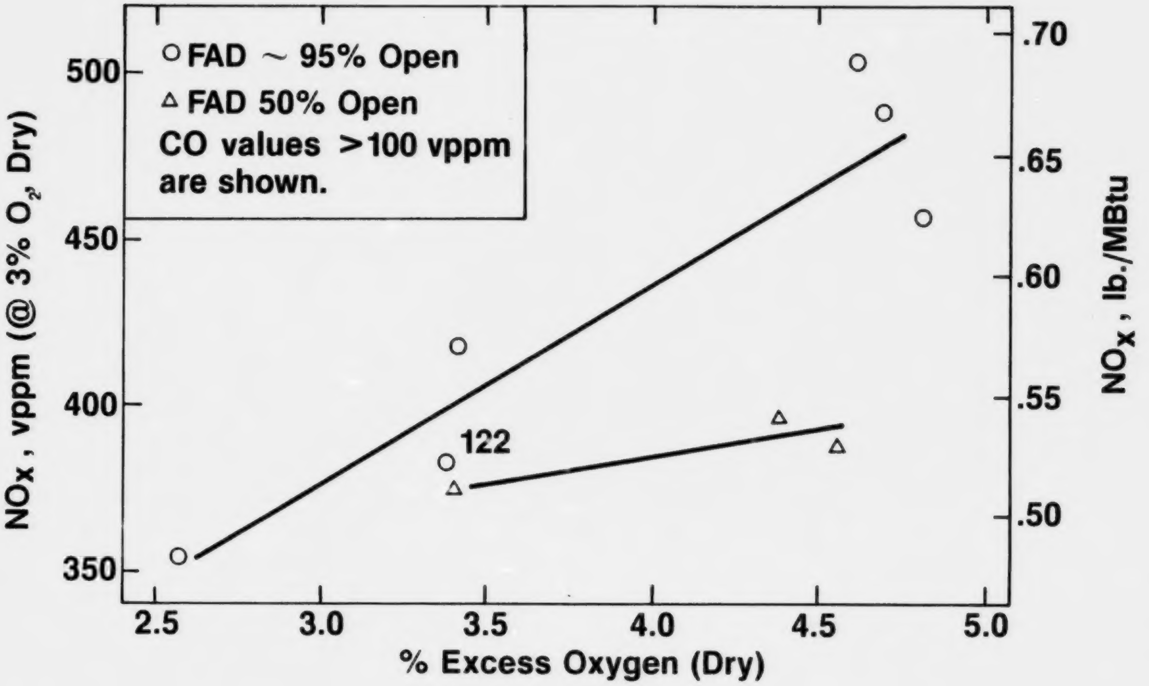

Figure C-6
Effect of Fuel Air Dampers on NO_x Levels

TABLE C-7
BASELINE CHARACTERIZATION TESTS
EFFECT OF FUEL AIR DAMPERS ON NOX LEVELS

≥ 93% OPEN FUEL AIR DAMPERS

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT 02	NOX VPPM	CO VPPM
14	395	5	96	5.5	0	0	0	5	21	60	21	4.70	488	62
22	392	5	93	5.0	0	0	0	4	21	60	21	4.62	503	17
24	390	5	93	3.7	0	0	0	2	0	60	0	2.56	355	16
37	411	5	98	4.7	0	0	0	0	0	60	0	3.38	382	122
40	413	5	98	5.0	0	0	0	0	29	60	29	4.82	457	13
41	411	5	98	5.0	0	0	0	0	20	60	20	3.41	418	14
50% OPEN FUEL AIR DAMPERS														
16	394	5	50	5.1	0	0	0	7	26	60	26	4.55	387	56
38	417	5	50	5.0	0	0	0	0	25	60	25	3.40	374	14
51	395	5	50	5.2	0	0	0	0	29	0	29	4.39	396	15

CONDITIONS:
LOAD = ~400 MWE;
5 FUEL ELEVATIONS IN SERVICE;
NO OFA;
BTILT = 0° ± 7°;
DATA USED IN FIGURE C-6.

the acronyms B4 and T4, respectively. For non-overfire air operation, B4 operation yielded NO_x levels ~60 vppm lower than T4 operation. For overfire air operation, B4 operation yielded NO_x levels ~75 vppm lower than T4 operation. In both cases, however, B4 tests were performed with burner tilts approximately 10° higher than for the T4 tests. This is result of automatic boiler controls attempting to maintain pre-determined steam temperatures. Therefore, these NO_x differences can be viewed as the result of actual operational differences between B4 and T4 operation.

III. CONCLUSIONS

NO_x levels during standard full load boiler operating conditions (i.e., 4.5% excess oxygen, no overfire air, and burner tilts of 0° ±5°) were approximately 460 vppm (0.63 lb/MBtu, 270 ng/J). These NO_x levels were effectively reduced through the use of combustion modifications, as summarized in Table C-8. Many boiler operating parameters have synergistic interrelationships in the way they control NO_x emissions. However, over the range tested, the effects of the various parameters are approximately additive and NO_x levels were effectively reduced to approximately 320 vppm (0.44 lb/MBtu, 189 ng/J) (without adversely affecting boiler operability) by decreasing excess oxygen levels to 3.5% (a 50 vppm NO_x reduction), by instituting the use of overfire air (a 75 vppm NO_x reduction), and by setting a moderate degree of angle differential (~15°) between the overfire air compartments and the fuel compartments (about a 15 vppm NO_x reduction).

TABLE C-8

BASELINE CHARACTERIZATION TESTING
NO_x REDUCTION LEVELS FOR VARIOUS OPERATING PARAMETERS
(Reductions in VPPM)

	~400 MW_e	~400 MW_e w/OFA	~300 MW_e	~300 MW_e w/OFA
• Excess Oxygen - NO_x reductions per 1% decrease in excess oxygen levels (down to 2.5% excess oxygen)	50	50	70	70
• Overfire Air - Low flow rate	-	<20	-	-
- Moderate flow rate	-	45	-	-
- High flow rate, typical operation(1)	-	75	-	>105
- High flow rate, atypical operation(1)	-	-	-	>115
• Load - NO_x reductions compared to full load levels	-	-	<15	~30
• Fuel Air Damper Settings - NO_x reductions for decreases from fully open position to 50% open	~50	-	-	-
• Burner (nozzle) Tilt - NO_x reductions per 10° decrease in burner tilt	25	-	-	-
• Differential Angle (i.e., the angle between the overfire air compartments and the fuel compartments) - NO_x reductions or a change of >30°	-	≤30	-	-
• Fuel Elevations in Service - NO_x reductions due to a change from top four operation to bottom four operation(2)	-	-	>60	>75

Notes:

(1) At 300 MW_e, high overfire air flow rate is ≥40% open for both overfire air elevations. Also, typical operation is considered the top four fuel elevations in service, while atypical operation is considered the bottom four fuel elevations in service.

(2) Comparative levels are based on equal burner tilts.

PART D

POST-MODIFICATION CHARACTERIZATION TESTING

I. INTRODUCTION

Post-modification characterization testing was designed to assess the effects of major windbox hardware modifications plus operational changes on NO_x emissions. These hardware changes, designated as Modifications 1, 2 and 3, respectively, are discussed in detail in Part A, Section IV. Following Modification 1, in which the C-E Low-NO_x Concentric Firing System (LNCFS) was installed in the windbox, test conditions were chosen in an attempt to evaluate parameters which might affect NO_x emissions (without adversely affecting boiler operation). During this phase, only full load testing was performed. This was because the potential for decreasing NO_x emissions (in terms of lb/hr as well as in terms of lb/MBtu) was estimated to be greatest at full load. Test results were compared with those from the baseline testing to determine the general effects of the LNCFS on NO_x levels, and also to evaluate whether the LNCFS had altered the parametric NO_x relationships established during baseline testing. Again, as in the case of the baseline testing, parametric effects on NO_x were shown to be strongly interrelated.

Following this first phase of post-modification testing, windbox Modification 2 was performed in an effort to further optimize the LNCFS and reduce NO_x levels. Emphasis for evaluating Modification 2 was placed on achieving optimum low-NO_x conditions (without adversely affecting boiler operation). Initially, most of the tests were conducted at full load in order to compare results with those for Modification 1 testing. However, when it was discovered that the near term (2-3 year) daytime load projections for the Hunter No. 2 Unit were for between 50 to 75% load, testing emphasis was shifted to define optimum low-NO_x conditions for this load range.

Results from Modification 2 testing demonstrated stronger parametric interrelationships which limited boiler operating flexibility for certain low-NO_x operating conditions. These stronger interrelationships also limited evaluation of certain parametric effects on NO_x levels. In response, a third modification was performed on the LNCFS to restore some of the boiler's operating flexibility at low-NO_x levels. For these tests, emphasis was placed on boiler stability and NO_x levels at the reduced loads (50-75% loads).

In order to fully test the windbox hardware modifications, the boiler was tested through a full range of previously untypical operating conditions. For comparative purposes, these operating conditions are listed below, along with the range of baseline test conditions and initial pre-test operating set points. Note, however, that under some of these conditions boiler stability could be maintained only for a short period of time before boiler operability was affected.

Parameter	Pre-test Set Points	Baseline Test Range	Post-modification Test Range
• Excess air (as % O_2 in flue gas)	4.5%	2.3% - 7.0%	2.3% - 6.3%
• Burner tilt (± degrees from horizontal)	0° ±5°	-20° to +18°	-23° to 30°
• Fuel air dampers (% open)	100%	100% to 50%	100% to 10%
• Auxiliary air dampers (% open)	~20%	0% to 37%	0% to 100%
• Bottom aux. air dampers (% open)	50%	0% to 60%	0% to 100%
• Overfire air dampers (% open)	0%	0% to 100%	0% to 100%
• Overfire air tilt (± degrees from horizontal)	Not Used	-10° to +30°	-10° to +30°
• LNCFS offset angle	Not Applicable	Not Applicable	+8° to +30°

As indicated above, the boiler combustion parameters investigated during the post-modification phases of testing were the same as in the baseline testing, except that the parameter "LNCFS offset angle" was added (discussed in Part A, Section IV). LNCFS offset angle was evaluated to determine if variations in the angle had a marked effect on NO_x levels, or whether NO_x levels were strongly related to the other boiler operating parameters.

As in the case of the baseline testing, the parametric interrelationships created by the boiler's automatic controls made it difficult to vary (and thus evaluate) only one parameter at a time. It was not known during testing, which unintentional changes (in other operating parameters) might effect NO_x emissions. Therefore, as stated in Part C of this report, determination of parametric relationships were reserved until after testing was completed. This explains why there is a disproportionate amount of data for the various parameters evaluated, and also why certain analyses exhibited a moderate degree of data scatter.

During the set-up period prior to each test (as previously discussed in Part C, Section I) when boiler operating conditions yielded preliminary pre-test CO levels of $\geq$ 100 vppm, the test was usually aborted and operating conditions were modified slightly to decrease the CO levels before proceeding. However, in some cases, tests were still run even though high CO levels were detected. These tests were conducted because as explained earlier it was deemed important to examine NO_x and/or CO trends at these unstable conditions (not recommended for long term operation).

II. RESULTS AND DISCUSSION

A total of 326 post-modification tests were performed, with the results from 323 of these tests yielding acceptable data. These results are shown in Table D-1. The data from three of the tests were discounted due to uncontrollable boiler changes during these tests. 154 tests were performed during two separate visits following Modification 1. 149 tests were performed in two visits following Modification 2. Also, twenty tests were performed in the final visit following Modification 3.

As discussed in the introduction to this section, different test goals were emphasized during each modification phase of testing. Also, during each modification phase, under certain sets of low-NO_x operating conditions, the boiler was not able to operate smoothly. In addition, in some cases, test results from the different modification phases were similar, and therefore, the results were combined in their analyses. Because of these conditions, quantitative parametric effects on NO_x have been defined in terms of general post-modification relationships. Distinctions between the modification phases have been made only qualitatively (when available), or when they are clearly defined quantitatively.

TABLE D-1 (PG 1 OF 9)
POST-MODIFICATION TEST RESULTS
UTAH POWER AND LIGHT CO.
HUNTER GENERATING STATION, UNIT NO. 2

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
Modification 1															
101	402	5	100	5.5	0	25	0	0	39	50	39	3.71	376	12	
102	399	5	100	3.7	0	25	0	-3	50	50	50	3.40	362	12	
103	404	5	100	4.0	50	25	0	-5	35	50	35	4.20	344	14	
104	405	5	100	4.5	50	25	0	-5	35	0	35	3.58	323	18	
105	406	5	100	6.0	0	25	0	-1	38	50	38	3.82	445	11	
106	406	5	100	5.0	0	33	0	1	40	0	40	3.75	434	12	
107	403	5	100	5.0	0	25	0	0	36	0	36	3.73	446	10	
108	331	4	100	5.0	0	25	0	0	20	0	20	3.57	347	12	1
109	332	4	100	2.5	0	25	0	0	35	0	35	3.32	372	11	1
110	332	4	100	3.0	0	25	0	0	30	0	30	2.35	293	34	1
111	407	5	100	3.5	0	25	0	0	48	0	48	3.07	407	12	
112	404	5	100	3.5	0	25	0	0	50	0	50	3.26	426	10	
113	405	5	100	3.5	0	25	0	0	41	0	41	2.36	383	12	
114	404	5	100	3.5	0	25	0	1	55	10	0	3.78	426	11	
116	401	5	100	5.5	100	25	0	0	38	10	0	5.26	373	12	
117	406	5	100	5.5	100	25	0	1	30	10	0	3.72	272	36	
118	400	5	100	5.5	0	25	0	0	50	0	0	3.55	406	11	
119	401	5	50	5.5	0	25	0	0	53	0	0	3.50	411	11	2
120	398	5	20	4.5	0	25	0	0	55	0	0	3.76	406	11	2
121	395	5	20	3.5	0	25	0	0	100	0	0	3.70	374	12	2
122	393	5	20	4.0	0	33	0	0	100	0	0	3.82	355	12	2
123	394	5	50	4.0	0	33	0	0	100	0	0	3.99	408	12	2
124	399	5	50	5.5	0	33	0	0	53	0	0	3.78	423	12	2
125	405	5	100	5.5	0	33	0	-5	40	50	40	3.82	462	10	
126	412	5	100	6.5	0	33	0	6	100	0	0	4.12	423	11	3
127	412	5	100	5.5	0	17	0	5	100	0	0	4.38	397	12	3
128	426	5	100	5.5	0	33	0	10	70	0	0	3.79	385	17	3
129	420	5	100	5.5	0	33	0	-2	60	0	0	3.88	445	10	
130	416	5	20	5.7	0	33	0	12	80	0	0	4.10	353	16	2
131	426	5	20	5.5	0	33	0	20	100	0	0	3.25	245	724	2
132	429	5	100	5.5	0	33	0	-4	50	0	0	2.95	392	13	
133	430	5	100	7.5	0	33	0	0	100	0	0	6.13	543	12	
134	419	5	100	5.0	50	33	0	10	65	0	0	4.82	391	13	
135	430	5	100	5.6	25	33	0	23	100	0	0	4.10	252	580	
136	421	5	100	4.6	20	17	0	25	100	0	0	4.00	296	265	
137	423	5	100	5.0	0	17	0	25	100	0	0	4.06	311	172	
138	425	5	10	5.6	0	17	0	23	45	0	0	4.09	318	122	2
139	424	5	20	5.5	0	17	0	21	68	0	0	4.20	335	53	2
140	421	5	10	5.5	0	17	0	-4	60	25	0	4.02	418	14	2

TABLE D-1 (PG 2 OF 9)
POST-MODIFICATION TEST RESULTS
UTAH POWER AND LIGHT CO.
HUNTER GENERATING STATION, UNIT NO. 2

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
141	422	5	10	5.5	0	33	0	18	100	25	0	4.28	304	140	2
142	424	5	10	5.5	0	33	0	19	97	100	0	4.56	316	84	2
143	421	5	10	5.7	0	33	0	20	100	100	0	4.53	317	83	4
144	423	5	10	5.6	0	25	0	26	100	100	0	4.83	315	98	4
145	423	5	10	5.5	0	17	0	18	65	100	0	3.80	335	67	4
146	420	5	15	5.6	0	17	0	23	81	100	0	5.10	387	54	4
147	402	5	50	5.7	0	17	0	0	39	60	100	4.22	494	23	4
148	402	5	50	5.7	0	17	0	0	55	100	0	4.48	477	102	4
149	428	5	20	5.5	0	17	0	7	68	100	0	4.67	442	47	4
150	421	5	10	5.5	0	17	0	23	100	100	0	5.46	398	107	4
151	425	5	10	5.8	0	17	0	27	80	100	0	2.60	304	31	4
152	422	5	20	5.6	0	17	0	27	100	100	0	2.55	335	22	4
153	428	5	50	5.5	0	17	0	18	46	100	0	3.60	324	132	4
154	425	5	20	5.5	0	17	0	14	50	100	0	3.49	306	257	4
155	424	5	10	5.5	0	17	0	13	60	100	0	3.42	320	194	4
156	426	5	100	5.5	0	17	0	0	46	100	0	3.38	394	18	
157	426	5	100	5.5	0	25	0	-10	46	100	0	3.63	452	19	
158	424	5	50	5.6	0	25	0	-4	50	100	0	3.71	441	21	4
159	426	5	20	5.5	0	25	0	-11	53	100	0	3.65	420	13	4
160	424	5	10	5.6	0	25	0	-8	60	100	0	3.58	402	22	4
161	421	5	10	5.7	0	33	0	20	100	100	0	4.30	280	416	4
162	426	5	20	5.5	0	33	0	14	94	100	0	4.06	313	236	4
163	424	5	50	5.5	0	33	0	0	58	100	0	3.84	426	22	4
164	427	5	100	5.5	0	33	0	-18	50	100	0	3.45	465	22	
165	419	5	100	5.5	0	33	0	19	100	100	0	5.54	390	104	5
166	422	5	50	5.5	0	33	0	19	71	100	0	4.43	366	---	4,6
167	422	5	20	5.5	0	33	0	19	80	100	0	4.14	309	276	4
168	418	5	10	6.5	0	33	0	19	100	100	0	4.08	271	464	4
169	424	5	50	5.5	0	33	0	16	60	100	0	4.00	360	53	4
170	426	5	100	5.5	0	33	0	6	60	100	0	4.46	430	14	
171	424	5	50	5.5	0	25	0	12	53	100	0	5.15	397	11	4
172	423	5	20	5.5	0	25	0	20	65	100	0	5.18	313	258	4
173	420	5	10	5.6	0	25	0	20	75	100	0	5.21	283	450	4
174	424	5	10	5.5	100	25	0	19	53	100	0	5.33	284	140	4,7
175	424	5	10	5.5	100	25	0	15	48	100	0	4.58	279	236	4,7
176	424	5	10	5.5	0	25	0	23	71	100	0	5.25	275	666	4
177	424	5	20	5.6	0	25	0	21	62	100	0	5.05	299	600	4
178	426	5	50	5.5	0	25	0	16	50	100	0	5.16	363	175	4
179	425	5	50	5.3	0	17	0	2	50	100	0	4.80	435	10	4
180	425	5	20	5.5	0	17	0	0	55	100	0	4.75	406	15	4
181	421	5	10	5.5	0	17	0	3	62	100	0	4.72	373	11	4

TABLE D-1 (PG 3 OF 9)
POST-MODIFICATION TEST RESULTS
UTAH POWER AND LIGHT CO.
HUNTER GENERATING STATION, UNIT NO. 2

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
182	423	5	20	5.6	0	17	0	19	70	100	0	6.28	324	20	4
183	416	5	10	6.5	0	33	0	18	100	100	0	6.31	338	71	4
184	413	5	20	6.0	0	33	0	18	100	100	0	6.27	342	34	4
185	413	5	20	5.5	0	25	0	19	89	100	0	5.99	342	76	4
186	421	5	10	5.5	0	25	0	23	91	100	0	5.80	323	152	
187	420	5	10	5.5	0	25	0	19	64	100	0	4.95	281	414	4
201	418	5	100	5.2	0	25	0	0	70	0	0	4.15	458	15	
202	428	5	100	5.6	100	25	0	0	45	0	0	3.79	327	32	
203	427	5	50	5.3	100	25	0	0	47	0	0	4.08	323	34	
204	418	5	20	5.6	100	25	0	0	49	0	0	4.14	309	14	
205	414	5	10	5.5	100	25	0	0	56	0	0	4.21	296	11	
206	419	5	100	3.7	100	25	0	0	70	0	0	4.16	323	18	
207	424	5	100	5.2	100	25	0	0	42	0	0	3.80	303	68	
208	423	5	100	5.5	50	25	0	0	48	0	0	3.98	341	16	
209	425	5	100	5.4	50	25	0	0	44	0	0	3.55	325	66	
210	422	5	50	5.5	50	25	0	0	45	0	0	3.65	311	31	
211	420	5	20	5.4	50	25	0	0	51	0	0	3.67	307	17	
212	414	5	10	5.3	50	25	0	0	60	0	0	3.90	300	22	
213	426	5	100	5.2	100	25	-10	-15	46	0	0	4.64	403	11	
214	418	5	100	5.5	100	25	10	9	44	0	0	3.96	287	192	
215	424	5	100	5.5	100	25	30	0	40	0	0	3.13	246	493	
216	422	5	100	5.5	100	25	30	-15	40	0	0	3.56	284	15	
217	420	5	100	5.5	100	25	30	0	37	0	0	3.44	277	393	
218	424	5	100	5.2	100	25	30	10	40	0	0	3.44	256	495	
219	420	5	100	5.6	100	25	30	-15	37	0	0	3.66	274	22	
220	416	5	11	5.4	100	25	30	-15	52	0	0	4.14	301	26	
221	425	5	11	5.6	100	25	30	10	56	0	0	4.07	244	>416	8
222	428	5	11	5.1	100	25	30	20	56	0	0	3.73	224	2973	
223	420	5	100	5.1	100	25	30	-15	39	0	0	4.46	327	15	
224	420	5	100	5.2	100	25	30	-15	45	0	0	4.64	383	28	
225	421	5	100	5.3	100	25	30	10	48	0	0	4.65	306	157	
226	416	5	10	5.4	100	25	30	20	70	0	0	4.88	245	894	
227	411	5	10	5.3	100	25	30	10	67	0	0	5.05	236	43	
228	410	5	10	5.0	100	25	30	-15	66	0	0	5.00	366	16	
229	421	5	10	5.4	100	25	0	18	55	0	0	4.55	298	193	
230	426	5	10	5.4	100	25	30	20	52	0	0	4.30	247	1285	
231	417	5	10	5.3	100	17	0	0	52	0	0	4.38	287	31	
232	422	5	20	5.4	100	17	0	0	46	0	0	4.29	296	20	
233	428	5	50	5.2	100	17	0	0	39	0	0	4.08	295	90	
234	427	5	100	5.5	100	17	0	0	36	0	0	3.37	270	>626	8
235	421	5	100	3.7	100	17	0	0	60	0	0	4.15	299	37	

TABLE D-1 (PG 4 OF 9)
POST-MODIFICATION TEST RESULTS
UTAH POWER AND LIGHT CO.
HUNTER GENERATING STATION, UNIT NO. 2

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT 02	NOX VPPM	CO VPPM	NOTES
236	420	5	100	5.4	100	17	0	0	35	0	0	3.79	268	1122	
237	420	5	100	5.4	100	33	0	0	44	0	0	4.58	346	45	
238	417	5	50	5.2	100	33	0	0	45	0	0	4.88	337	41	
239	415	5	20	5.3	100	33	0	0	50	0	0	4.96	334	23	
240	415	5	10	5.4	100	33	0	0	56	0	0	4.86	347	16	
241	425	5	10	5.3	100	33	0	0	40	50	40	4.56	346	15	
242	425	5	100	5.4	0	33	0	0	48	50	48	4.13	489	12	
243	409	5	100	5.4	0	33	0	0	46	50	46	4.35	485	23	
244	411	5	100	5.4	100	33	0	0	34	0	0	4.69	290	860	
245	411	5	100	5.5	100	33	0	0	29	100	0	3.70	261	271	
246	411	5	100	5.3	100	33	0	0	35	0	0	4.03	256	2250	
247	410	5	50	5.4	100	33	0	0	36	0	0	4.19	269	1299	
248	412	5	20	5.4	100	33	0	0	40	0	0	4.30	266	272	
249	410	5	10	5.2	100	33	0	0	47	0	0	4.78	260	217	
250	---	5	100	6.0	0	17	0	0	100	0	0	2.59	353	18	9
251	---	5	100	4.5	100	17	0	0	65	0	0	4.46	296	38	9
252	---	5	100	7.0	0	33	0	0	100	0	0	3.95	452	14	9
253	---	5	100	6.0	0	17	0	0	100	0	0	4.03	373	15	9
254	418	5	100	5.5	100	17	30	0	35	0	0	3.92	269	154	
255	418	5	100	5.5	100	17	30	-15	30	0	0	3.61	247	194	
256	423	5	100	5.6	100	17	30	0	43	0	0	4.30	299	43	
257	433	5	100	5.4	100	25	30	-13	36	0	0	3.37	269	329	
258	432	5	100	5.5	100	25	30	0	35	0	0	3.70	263	438	
259	434	5	100	6.0	100	25	30	0	35	0	0	4.08	287	179	
260	425	5	100	6.0	100	17	30	0	30	50	0	4.07	266	70	
261	420	5	100	5.7	100	17	30	-15	26	50	0	4.19	242	8	
262	420	5	100	6.3	100	17	30	-15	26	50	0	4.21	246	28	
263	426	5	100	5.8	100	17	30	-15	30	0	0	3.87	251	268	
264	419	5	100	6.1	100	17	30	-15	26	0	26	3.92	235	100	
265	419	5	100	6.2	100	17	30	-15	20	50	20	4.29	255	26	
266	385	5	100	5.5	100	17	30	-15	12	50	12	3.81	220	39	
268	420	5	100	6.1	100	17	30	-23	30	0	30	4.42	266	29	
269	420	5	100	5.9	100	17	30	-23	30	0	30	4.51	257	31	
						Modification 2									
301	402	5	100	5.5	100	33	30	-4	23	50	23	3.96	264	43	
302	398	5	100	5.5	100	33	30	-15	20	50	20	3.69	250	62	
303	399	5	100	5.5	100	33	30	-15	16	50	16	3.20	221	61	
304	399	5	100	5.5	100	33	30	-15	16	50	16	3.38	233	90	
305	398	5	100	5.5	100	33	30	0	20	50	20	3.38	245	115	10

TABLE D-1 (PG 5 OF 9)
POST-MODIFICATION TEST RESULTS
UTAH POWER AND LIGHT CO.
HUNTER GENERATING STATION, UNIT NO. 2

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
306	400	5	100	5.5	100	33	30	0	30	50	30	4.45	255	44	
307	401	5	100	5.5	100	33	30	15	30	50	30	4.39	215	139	
308	402	5	100	5.5	100	33	30	15	25	50	25	3.59	204	151	
309	425	5	100	5.5	0	17	0	5	45	50	45	2.82	291	85	
310	412	5	100	5.5	100	17	30	-5	20	50	20	2.99	201	387	
311	411	5	100	5.5	100	17	30	-16	24	50	24	3.68	240	193	
312	407	5	100	5.5	100	17	30	-16	20	100	20	3.54	230	136	
313	408	5	100	5.5	100	33	30	-16	16	100	16	2.71	197	435	
314	417	5	100	5.5	100	17	0	16	24	100	24	3.60	300	106	
315	416	5	100	5.5	100	17	0	0	25	100	25	3.39	288	40	
316	416	5	100	5.5	100	17	0	0	20	100	20	2.26	258	115	
317	412	5	100	5.5	100	33	0	0	14	100	14	2.41	254	56	
318	412	5	100	5.5	100	33	0	0	14	100	14	2.46	248	95	
319	416	5	100	5.5	100	33	0	0	22	25	22	2.43	248	55	
320	380	5	100	5.5	100	17	30	20	15	50	15	3.60	224	153	
321	381	5	100	5.5	100	17	30	0	12	50	12	3.20	206	84	
322	377	5	100	5.5	100	17	30	-15	8	50	8	3.58	199	64	
323	370	5	100	5.5	100	17	30	-15	0	50	0	3.40	197	82	11
324	372	5	100	5.5	100	25	30	24	9	50	9	3.29	242	71	
325	369	5	100	5.5	100	25	30	0	12	50	12	3.41	212	104	
326	379	5	100	5.5	100	25	30	-15	4	50	4	3.52	205	45	
327	370	5	100	5.5	100	25	30	-15	0	50	0	3.11	180	124	12
328	374	5	100	5.5	100	25	30	-15	0	50	0	3.04	179	84	
329	378	5	100	5.5	100	25	30	-15	12	50	12	4.66	239	51	12
330	369	5	100	5.5	100	17	30	-17	0	50	0	3.46	202	38	
331	427	5	100	5.5	100	17	30	-15	28	50	28	3.47	236	111	
332	427	5	100	5.5	100	17	30	-15	27	50	27	4.60	302	29	
333	428	5	100	9.0	100	17	30	-15	17	50	17	4.91	285	25	
334	430	5	100	6.0	100	17	30	-15	26	50	26	4.08	276	43	
335	427	5	100	5.5	100	17	0	-15	30	50	30	3.66	268	66	
336	430	5	100	5.5	100	17	-5	-15	30	50	30	3.69	276	48	
337	422	5	100	5.5	100	5	15	0	28	50	28	4.39	250	81	
338	421	5	100	5.5	0	5	0	0	44	50	44	4.03	340	56	
339	420	5	100	5.5	0	25	0	0	48	50	48	4.06	385	56	
340	423	5	100	5.5	100	25	0	15	24	50	24	3.56	292	81	
341	423	5	100	5.5	100	25	0	15	24	50	24	3.19	280	100	
342	417	5	100	5.5	100	25	0	0	24	50	24	3.12	265	58	
343	419	5	100	5.5	100	25	0	0	14	50	14	2.75	229	150	13
344	414	5	100	5.5	100	25	0	0	12	50	12	2.92	244	73	14
345	419	5	100	5.5	100	25	15	0	20	50	20	3.37	227	183	14
346	410	5	100	5.5	100	17	15	0	14	50	14	3.21	204	190	14

TABLE D-1 (PG 6 OF 9)
POST-MODIFICATION TEST RESULTS
UTAH POWER AND LIGHT CO.
HUNTER GENERATING STATION, UNIT NO. 2

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
347	419	5	100	5.5	100	17	0	0	24	50	24	3.91	262	65	14
348	417	5	100	5.5	100	17	0	10	22	50	22	3.87	265	144	14
349	417	5	100	5.5	100	17	0	-10	20	50	20	3.82	249	62	14
350	419	5	100	5.5	100	17	0	-10	14	50	14	3.13	232	68	14
351	429	5	100	5.5	100	17	0	20	32	50	32	4.40	306	75	15
352	428	5	100	5.5	100	17	0	-5	20	50	20	3.20	233	118	14
353	404	5	100	5.5	100	17	0	-3	20	50	20	4.11	250	61	15
354	387	5	100	5.5	100	17	0	22	10	50	10	3.40	303	177	15
355	369	5	100	5.5	62	17	0	20	10	50	10	3.32	269	87	15
356	360	5	80	5.5	53	17	0	18	11	50	11	3.14	250	474	15
357	337	5	70	4.5	48	17	0	12	14	50	14	3.34	254	464	15
358	321	5	50	4.0	30	17	0	-5	17	50	17	3.58	255	689	15
359	296	4	50	3.5	0	17	0	-7	35	50	35	4.51	364	54	15, 16
360	370	5	100	5.5	0	17	0	-10	32	50	32	4.32	369	57	15
361	371	5	100	5.2	0	17	0	20	38	50	38	5.25	334	63	15
362	299	4	80	3.3	0	17	0	24	35	50	35	4.50	294	65	15, 16
363	296	4	70	3.7	0	17	0	24	31	50	31	3.71	281	110	15, 16
364	203	3	50	1.2	0	17	0	30	42	50	42	6.11	293	65	15, 17
365	203	3	50	2.0	0	17	0	20	22	50	22	4.85	278	62	15, 17
366	203	3	50	2.5	58	17	0	12	11	50	11	4.90	227	63	15, 17
367	377	5	90	5.5	100	17	0	5	18	50	18	4.34	278	53	15
368	355	5	90	5.5	100	17	0	4	0	50	0	3.88	267	67	15
369	331	5	90	4.5	100	17	0	8	0	50	0	3.88	270	82	15
370	424	5	96	5.0	100	8	12	10	34	50	34	3.68	210	674	
371	382	5	95	5.5	0	8	0	10	37	50	37	4.05	298	222	
372	384	5	90	5.5	100	8	0	10	17	50	17	4.35	283	70	
373	350	5	90	5.0	100	8	0	13	6	50	6	3.93	280	70	
374	322	5	90	4.0	100	8	0	20	0	50	0	4.02	288	88	
375	353	5	90	4.5	100	8	0	20	0	50	0	3.72	279	73	
376	355	5	90	5.5	100	8	10	10	0	50	0	3.68	244	72	
377	349	5	90	5.0	100	8	10	10	0	50	0	3.68	233	71	
378	335	5	90	5.0	0	8	0	10	30	50	30	3.88	288	120	
379	320	4	90	5.0	0	8	0	10	30	50	30	4.49	327	102	16, 18
380	314	4	90	5.0	0	8	0	20	35	50	35	4.40	290	95	16
381	313	4	90	5.0	0	8	0	5	35	50	35	4.64	327	59	16
382	315	4	90	3.7	0	8	0	20	33	50	33	4.58	298	70	16
383	322	4	90	5.2	100	8	10	5	12	50	12	4.31	229	68	16
384	335	4	90	4.5	100	8	0	7	10	50	10	4.01	251	50	16
385	330	4	90	3.5	100	8	10	7	0	50	0	3.85	222	51	16
386	375	5	90	5.5	100	8	10	18	5	50	5	3.61	245	65	
387	375	5	90	5.5	100	8	10	12	5	50	5	3.52	224	55	

TABLE D-1 (PG 7 OF 9)
POST-MODIFICATION TEST RESULTS
UTAH POWER AND LIGHT CO.
HUNTER GENERATING STATION, UNIT NO. 2

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
388	375	5	90	5.5	100	8	10	20	0	50	0	3.72	251	60	
389	375	5	90	5.5	100	8	10	11	10	50	10	3.60	236	62	
390	375	5	90	5.6	100	8	10	5	10	50	10	3.46	211	56	
391	375	5	90	5.6	100	8	10	0	8	50	8	3.40	200	57	
392	375	5	90	5.6	100	8	10	-5	5	50	5	3.49	192	60	
393	371	5	100	5.5	100	8	10	17	6	50	6	3.64	241	54	
394	351	5	90	5.4	100	8	10	24	0	50	0	3.84	279	46	
395	350	5	90	5.4	100	8	10	23	0	50	0	3.72	280	55	
396	352	5	90	5.2	100	8	10	20	0	50	0	3.45	264	53	
397	350	5	90	5.2	100	8	10	20	0	50	0	3.31	253	56	
398	350	5	90	5.2	100	8	10	18	0	50	0	3.24	252	53	
399	352	5	90	5.6	100	8	10	10	0	50	0	3.68	247	56	
400	354	5	90	4.8	100	8	10	27	0	50	0	3.88	286	68	
401	350	5	90	4.8	100	8	10	23	0	50	0	3.78	282	58	
402	354	5	90	4.8	100	8	10	18	0	50	0	3.38	257	60	
403	350	5	90	4.8	100	8	10	18	0	50	0	3.42	261	60	
404	353	5	90	4.6	100	8	10	17	0	50	0	3.32	252	60	
405	356	5	90	4.6	100	8	10	17	0	50	0	3.01	243	57	
501	280	5	100	---	50	8	10	10	-	50	-	3.80	219	28	19,20
502	285	4	100	---	100	8	10	15	-	50	-	3.91	264	22	16,20
503	285	4	100	---	100	8	10	15	-	50	-	3.02	237	33	16,20
504	320	5	100	3.1	100	8	10	20	0	50	0	3.05	247	19	20
505	320	5	100	3.4	100	8	10	17	0	50	0	3.02	241	21	20
506	320	5	100	3.3	100	8	10	16	0	50	0	3.07	241	24	20
507	321	5	100	3.2	100	8	10	15	0	50	0	3.05	239	27	20
508	320	5	100	3.0	100	8	10	18	0	50	0	3.12	254	21	20
509	310	5	100	2.5	100	8	10	19	0	50	0	3.09	244	22	20
510	310	5	100	3.3	100	8	20	18	0	50	0	3.26	219	45	20
[illegible]	327	5	100	3.5	100	8	20	17	0	50	0	3.17	217	56	20
[illegible]	325	5	100	3.6	100	8	30	16	0	50	0	2.88	199	404	20,21
513	327	5	100	4.0	100	8	10	14	0	0	0	3.28	232	44	20
514	326	5	100	3.7	100	8	10	13	0	100	0	3.61	248	28	20
515	326	5	100	4.4	0	8	0	12	18	40	18	5.23	357	31	20
516	327	5	100	6.5	0	8	0	10	6	40	6	5.09	379	31	20
517	326	5	100	4.1	100	8	10	9	0	40	0	4.00	245	24	20
518	430	5	100	5.0	100	8	10	23	12	40	12	3.43	281	34	20
519	436	5	100	5.2	100	8	10	22	12	40	12	3.47	284	27	20
520	429	5	100	5.2	100	8	10	22	14	40	14	3.77	280	29	20
521	437	5	100	5.2	100	8	10	22	13	40	13	3.60	274	25	20
522	320	4	100	4.5	70	8	0	15	5	40	5	4.15	300	26	16,20
523	320	4	100	4.5	70	8	0	19	5	40	5	4.26	321	58	16,20
524	320	4	100	4.5	70	8	0	10	2	40	2	3.76	278	28	16,20

TABLE D-1 (PG 8 OF 9)
POST-MODIFICATION TEST RESULTS
UTAH POWER AND LIGHT CO.
HUNTER GENERATING STATION, UNIT NO. 2

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
525	320	4	100	4.5	70	8	10	23	2	40	2	4.12	284	135	16,20
526	320	4	100	4.5	70	8	10	18	2	40	2	3.61	275	32	16,20
527	320	4	100	4.5	70	8	10	13	8	40	8	4.74	277	17	16,20
528	320	4	100	4.5	0	8	0	15	24	40	24	5.38	345	48	16,20
529	323	4	100	4.5	0	8	0	20	20	40	20	4.96	329	33	16,20
531	186	3	100	3.0	0	8	0	26	10	40	10	6.34	308	26	17,20
532	191	3	100	2.5	0	8	0	26	10	40	10	5.68	272	27	17,20
533	190	3	100	2.5	0	8	0	26	10	40	10	5.79	276	26	17,20
534	273	4	100	3.5	0	8	0	24	12	40	12	4.53	344	31	16,20
535	321	4	100	4.0	100	8	10	25	0	40	0	3.76	305	36	16,20,22
536	317	4	100	4.6	50	8	10	23	0	40	0	3.55	287	27	16,20,22
537	314	5	100	3.4	50	8	10	24	0	40	0	3.11	251	31	20
538	314	5	100	2.8	100	8	10	23	0	40	0	3.39	265	22	20
539	310	4	100	4.1	100	8	10	23	0	40	0	3.06	212	55	20
540	313	4	100	4.0	50	8	10	22	0	40	0	2.84	198	169	20,23,24
541	314	4	100	4.1	50	8	10	22	0	40	0	2.77	195	781	20,23,24
542	325	5	100	4.5	50	8	10	23	1	40	1	3.23	264	50	20
543	320	4	100	4.4	50	8	10	23	5	40	5	3.87	275	37	16,20
544	321	4	100	4.3	50	8	10	23	3	40	3	3.45	264	65	16,20
545	320	4	100	4.3	50	8	10	23	2	40	2	3.67	263	124	16,20
Modification 3															
601	324	4	100	3.8	100	8	3	7	0	25	0	3.32	263	24	16
602	325	4	100	3.9	100	8	3	12	0	25	0	3.78	259	19	16
603	308	4	100	2.8	100	8	3	0	0	25	0	3.40	258	39	16
604	310	4	100	3.9	0	8	0	21	24	25	24	3.61	315	660	10,16
605	319	4	100	4.2	0	8	0	0	26	25	26	3.79	319	23	16
606	318	4	100	3.5	100	8	3	0	0	25	0	4.06	275	25	16
607	321	4	100	4.2	100	8	10	9	0	25	0	3.77	247	33	16
608	323	4	100	3.7	100	8	10	-10	0	25	0	3.13	206	45	16
609	320	4	100	4.1	100	8	10	-15	0	25	0	3.94	226	24	16
610	290	4	100	2.8	100	8	5	12	0	25	0	3.51	277	28	16
611	316	4	100	3.5	100	8	5	9	2	25	2	4.19	287	26	16
612	312	4	100	4.0	35	8	5	20	16	25	16	4.26	314	381	16
613	323	4	100	4.2	60	8	5	16	0	25	0	3.59	308	27	16
614	297	4	100	3.6	60	8	5	14	0	25	0	3.42	286	19	16
615	273	4	100	2.3	60	8	5	22	0	25	0	4.22	298	20	16,19
616	312	4	100	4.0	0	8	0	25	20	25	20	4.33	324	37	1
617	310	4	100	4.4	0	8	0	0	22	25	22	4.25	338	20	1
618	270	4	100	2.9	0	8	0	0	23	25	23	4.80	358	17	16
619	270	4	100	3.0	0	8	0	16	16	25	16	4.22	354	27	16
620	261	4	100	2.6	0	8	0	25	19	25	19	4.59	361	25	16

TABLE D-1 (PG 9 OF 9)
POST-MODIFICATION TEST RESULTS
UTAH POWER AND LIGHT CO.
HUNTER GENERATING STATION, UNIT NO. 2

Notes:

1. Mill No. 4 out of service.
2. TOP FAD open 100%.
3. AUX AIR compartment 2-3 closed.
4. Due to ignition point encroachment, the elevation 1 left rear burner's FAD was opened to 100%.
5. CO reading suspect due to a possible rotameter leak.
6. CO rotameter being serviced.
7. Lower OFA compartment closed.
8. CO scale not properly set for one of the probe assemblies; therefore, a > symbol has been added.
9. Load readings were not taken, however, loads were ~415 MWe.
10. High oxygen imbalance.
11. Oxygen levels were just at the point where instantaneous CO spikes were observed.
12. Oxygen imbalance levels switched duct sides during the test.
13. Top auxiliary air compartments (AUX 1) were 100% open.
14. Top auxiliary air compartments (AUX 1) were 100% open and at an 8 degree offset angle.
15. Top auxiliary air compartments (AUX 1) on automatic, and at an 8 degree offset angle.
16. Upper four fuel elevations used.
17. Middle three fuel elevations used.
18. Oxygen level in probe assemble no. 4 vascillated between 3.5% and 7.0% during the test.
19. Mill No. 3 out of service.
20. Left front burners on elevations 4 and 5, and the right rear burner on elevation 5 were at horizontal orientations (0 degrees) due to broken linkages.
21. Oxygen split was 2.4% right duct, 3.9% left duct when they flip-flopped, then eventually evened up at 3.2%.
22. Primary air was flowing throught the elevation 5 burners in anticipation of a load (and mill) increase.
23. Lower four fuel elevations used.
24. Oxygen and CO levels fluctuated drastically during these tests.

In the following discussions, the degree of staging is frequently referred to in overfire air test analyses. For the purpose of this report, the degree of staging is defined as the magnitude of the angle differential between the overfire air compartments tilts and the burner (nozzle) tilts. Angle differential values and their associated degree of staging include the following: deep staging ($\geq$40°), moderate staging (approximately 30° ±5°), average staging (about 0° ±5°), and minimal staging ($\leq$-5°).

A. Effect of Excess Oxygen on NO_x Levels

As discussed in Part A, Section IV, a reduction in excess air fired reduces the amount of air available in the combustion zone, and thus, should decrease NO_x emissions. This relationship was demonstrated during baseline testing and is also shown for post-modification testing in Figures D-1 through D-4. The data used in these figures are listed in Tables D-2 through D-5, respectively. As explained earlier all relevant data points, including those with high CO values (> 100 vppm) have been included in this analysis because they help to present a more complete picture of boiler cause-and-effect relationships. However, for the readers convience, in each figure, data points with high CO readings have been tagged by including the CO reading next to the corresponding data point. This format is continued throughout Parts C and D of this report.

Figure D-1 depicts combined Modifications 1 and 2 full load test results for overfire air tests (run at average to moderate degrees of staging) and for non-overfire air tests. Results show NO_x reductions of approximately 60 vppm per 1% decrease in excess oxygen levels for both overfire air and non-overfire air operation. Also, in Figure D-2, combined Modification 1 and 2 data for overfire air tests run at deep staging conditions at both full load (398-430 MW_e) and slightly lower loads (369-385

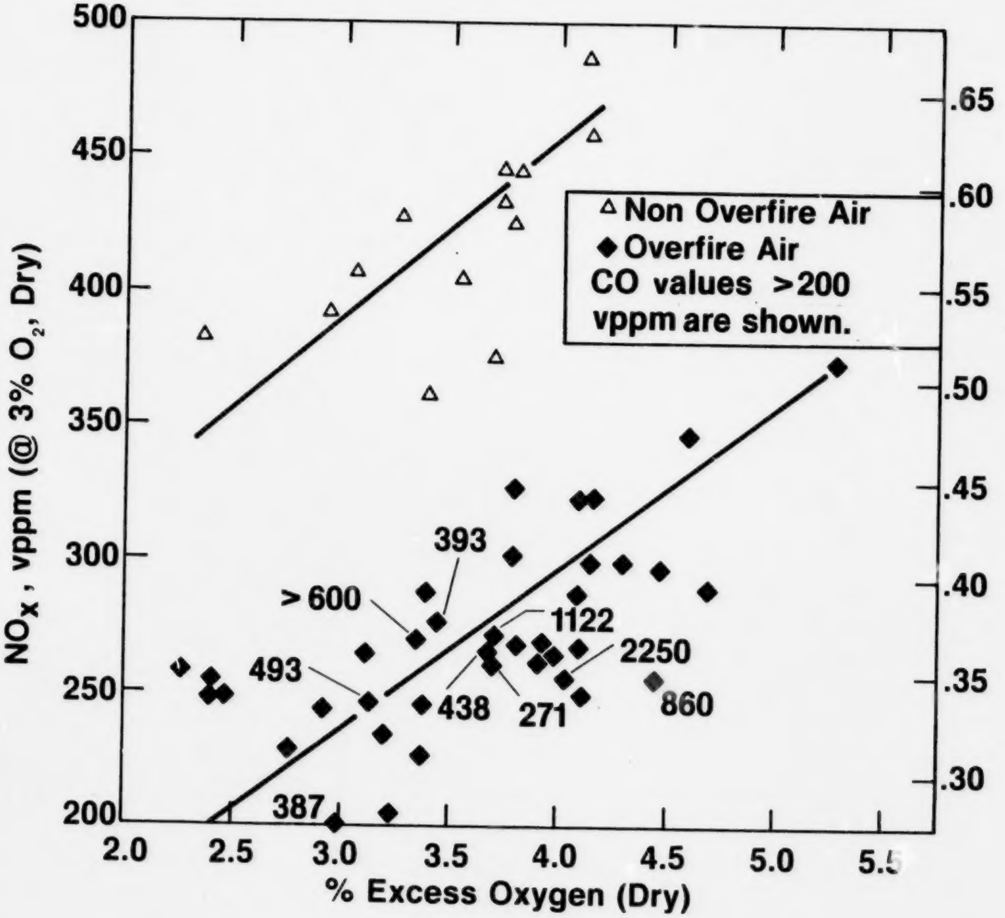

Figure D-1
Effect of Excess Oxygen on NO_X Levels:
Full Load Operation, with and without Overfire Air (Modification 1 and 2 Data)

1084-3-340

TABLE D-2 (PG 1 OF 2)
DATA FOR FIGURE D-1
EFFECT OF EXCESS OXYGEN ON NOx LEVELS:
FULL LOAD OPERATION, WITH OVERFIRE AIR (AVERAGE TO MODERATE STAGING), AND WITHOUT OVERFIRE AIR
(MODIFICATION 1 AND 2 DATA ONLY)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
Non-Overfire Air															
101	402	5	100	5.5	0	25	0	0	39	50	39	3.71	376	12	
102	399	5	100	3.7	0	25	0	-3	50	50	50	3.40	362	12	
105	406	5	100	6.0	0	25	0	-1	38	50	38	3.82	445	11	
106	406	5	100	5.0	0	33	0	1	40	0	40	3.75	434	12	
107	403	5	100	5.0	0	25	0	0	36	0	36	3.73	446	10	
111	407	5	100	3.5	0	25	0	0	48	0	48	3.07	407	12	
112	404	5	100	3.5	0	25	0	0	50	0	50	3.26	426	10	
113	405	5	100	3.5	0	25	0	0	41	0	41	2.36	383	12	
114	404	5	100	3.5	0	25	0	1	55	10	0	3.78	426	11	
118	400	5	100	5.5	0	25	0	0	50	0	0	3.55	406	11	
122	393	5	20	4.0	0	33	0	0	100	0	0	3.82	355	12	1
201	418	5	100	5.2	0	25	0	0	70	0	0	4.15	458	15	
242	425	5	100	5.4	0	33	0	0	48	50	48	4.13	489	12	
Overfire Air															
116	401	5	100	5.5	100	25	0	0	38	10	0	5.26	373	12	
117	406	5	100	5.5	100	25	0	1	30	10	0	3.72	272	36	
202	428	5	100	5.6	100	25	0	0	45	0	0	3.79	327	32	
203	427	5	50	5.3	100	25	0	0	47	0	0	4.08	323	34	
206	419	5	100	3.7	100	25	0	0	70	0	0	4.16	323	18	
207	424	5	100	5.2	100	25	0	0	42	0	0	3.80	303	68	
215	424	5	100	5.5	100	25	30	0	40	0	0	3.13	246	493	
217	420	5	100	5.5	100	25	30	0	37	0	0	3.44	277	393	
234	427	5	100	5.5	100	17	0	0	36	0	0	3.37	270	>626	2
235	421	5	100	3.7	100	17	0	0	60	0	0	4.15	299	37	
236	420	5	100	5.4	100	17	0	0	35	0	0	3.79	268	1122	
237	420	5	100	5.4	100	33	0	0	44	0	0	4.58	346	45	
244	411	5	100	5.4	100	33	0	0	34	0	0	4.69	290	860	
245	411	5	100	5.5	100	33	0	0	29	100	0	3.70	261	271	
246	411	5	100	5.3	100	33	0	0	35	0	0	4.03	256	2250	
251	---	5	100	4.5	100	17	0	0	65	0	0	4.46	296	38	3
254	418	5	100	5.5	100	17	30	0	35	0	0	3.92	269	154	
256	423	5	100	5.6	100	17	30	0	43	0	0	4.30	299	43	
258	432	5	100	5.5	100	25	30	0	35	0	0	3.70	263	438	
259	434	5	100	6.0	100	25	30	0	35	0	0	4.08	287	179	
260	425	5	100	6.0	100	17	30	0	30	50	0	4.07	266	70	
301	402	5	100	5.5	100	33	30	-4	23	50	23	3.96	264	43	
305	398	5	100	5.5	100	33	30	0	20	50	20	3.38	245	115	4
306	400	5	100	5.5	100	33	30	0	30	50	30	4.45	255	44	
310	412	5	100	5.5	100	17	30	-5	20	50	20	2.99	201	387	

TABLE D-2 (PG 2 OF 2)
DATA FOR FIGURE D-1
EFFECT OF EXCESS OXYGEN ON NOx LEVELS:
FULL LOAD OPERATION, WITH OVERFIRE AIR (AVERAGE TO MODERATE STAGING), AND WITHOUT OVERFIRE AIR
(MODIFICATION 1 AND 2 DATA ONLY)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
315	416	5	100	5.5	100	17	0	0	25	100	25	3.39	288	40	
316	416	5	100	5.5	100	17	0	0	20	100	20	2.26	258	115	
317	412	5	100	5.5	100	33	0	0	14	100	14	2.41	254	56	
318	412	5	100	5.5	100	33	0	0	14	100	14	2.46	248	95	
319	416	5	100	5.5	100	33	0	0	22	25	22	2.43	248	55	
342	417	5	100	5.5	100	25	0	0	24	50	24	3.12	265	58	
343	419	5	100	5.5	100	25	0	0	14	50	14	2.75	229	150	5
344	414	5	100	5.5	100	25	0	0	12	50	12	2.92	244	73	6
345	419	5	100	5.5	100	25	15	0	20	50	20	3.37	227	183	6
346	410	5	100	5.5	100	17	15	0	14	50	14	3.21	204	190	6
347	419	5	100	5.5	100	17	0	0	24	50	24	3.91	262	65	6
352	428	5	100	5.5	100	17	0	-5	20	50	20	3.20	233	118	6
353	404	5	100	5.5	100	17	0	-3	20	50	20	4.11	250	61	7

Notes:

1. Top FAD open 100%.
2. CO scale not properly set for one of the probe assemblies; therefore, a > symbol has been added.
3. Load reading not taken, however, loads were ~415 MWe.
4. High oxygen imbalance.
5. Top auxiliary air compartments (AUX 1) were 100% open.
6. Top auxiliary air compartments (AUX 1) were 100% open, and at an 8 degree offset angle.
7. Top auxiliary air compartments (AUX 1) were on automatic, and at an 8 degree offset angle.

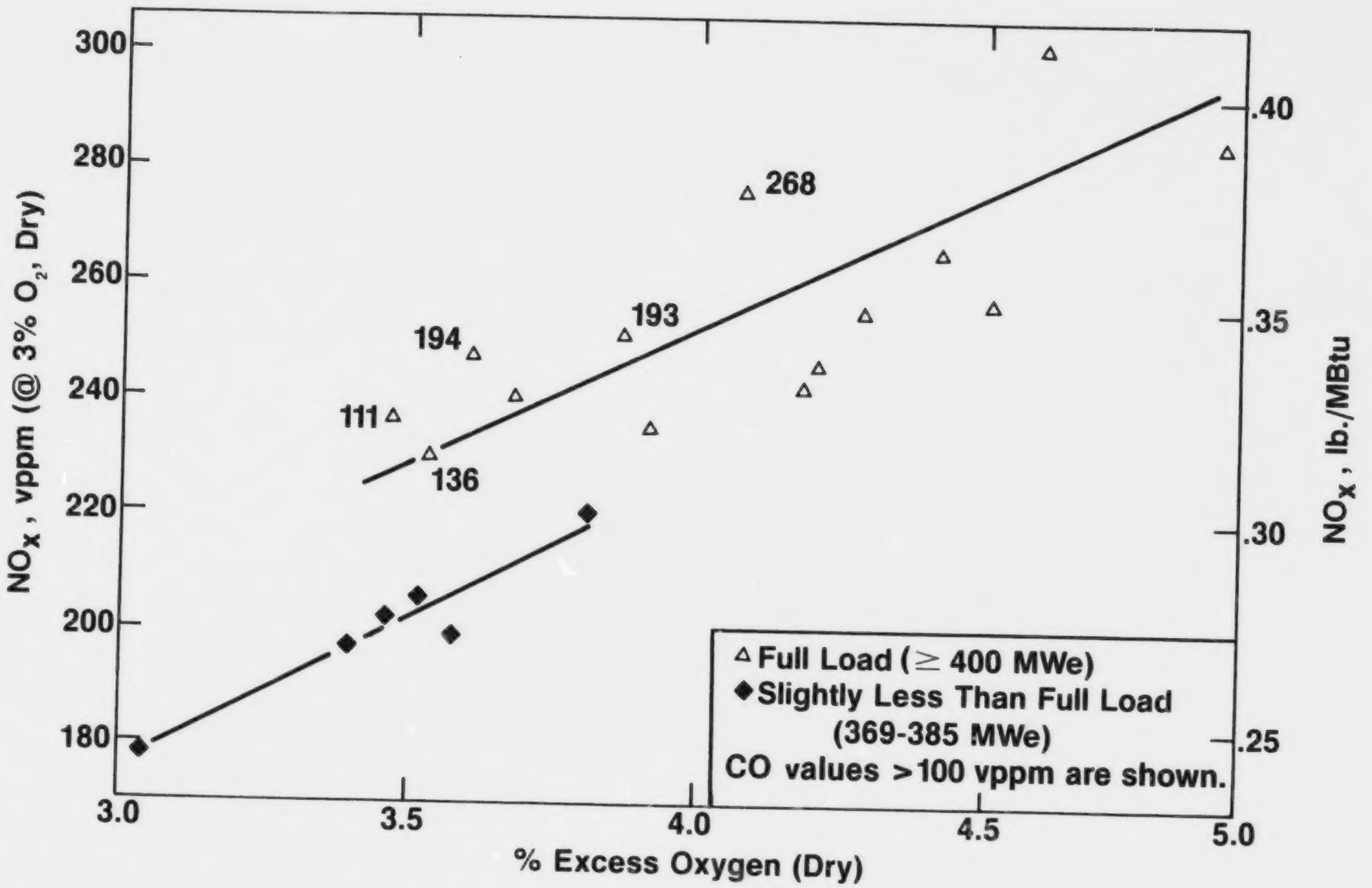

Figure D-2
Effect of Excess Oxygen on NO$_x$ Levels: Overfire Air Operation, Full and Near-Full Load (Modification 1 and 2 Data Only)

TABLE D-3
DATA FOR FIGURE D-2
EFFECT OF EXCESS OXYGEN ON NOX LEVELS: OVERFIRE AIR (DEEP STAGING) OPERATION, FULL AND NEAR-FULL LOAD
(MODIFICATION 1 AND 2 DATA ONLY)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
Full Load															
255	418	5	100	5.5	100	17	30	-15	30	0	0	3.61	247	194	
261	420	5	100	5.7	100	17	30	-15	26	50	0	4.19	242	8	
262	420	5	100	6.3	100	17	30	-15	26	50	0	4.21	246	28	
263	426	5	100	5.8	100	17	30	-15	30	0	0	3.87	251	268	
264	419	5	100	6.1	100	17	30	-15	26	0	26	3.92	235	100	
265	419	5	100	6.2	100	17	30	-15	20	50	20	4.29	255	26	
268	420	5	100	6.1	100	17	30	-23	30	0	30	4.42	266	29	
269	420	5	100	5.9	100	17	30	-23	30	0	30	4.51	257	31	
311	411	5	100	5.5	100	17	30	-16	24	50	24	3.68	240	193	
312	407	5	100	5.5	100	17	30	-16	20	100	20	3.54	230	136	
331	427	5	100	5.5	100	17	30	-15	28	50	28	3.47	236	111	
332	427	5	100	5.5	100	17	30	-15	27	50	27	4.60	302	29	
333	428	5	100	9.0	100	17	30	-15	17	50	17	4.91	285	25	
334	430	5	100	6.0	100	17	30	-15	26	50	26	4.08	276	43	
Slightly Less Than Full Load															
266	385	5	100	5.5	100	17	30	-15	12	50	12	3.81	220	39	
322	377	5	100	5.5	100	17	30	-15	8	50	8	3.58	199	64	
323	370	5	100	5.5	100	17	30	-15	0	50	0	3.40	197	82	1
326	379	5	100	5.5	100	25	30	-15	4	50	4	3.52	205	45	
328	374	5	100	5.5	100	25	30	-15	0	50	0	3.04	179	84	
330	369	5	100	5.5	100	17	30	-17	0	50	0	3.46	202	38	

NOTE:

1. Oxygen levels were just at the point where instantaneous CO spikes were experienced.

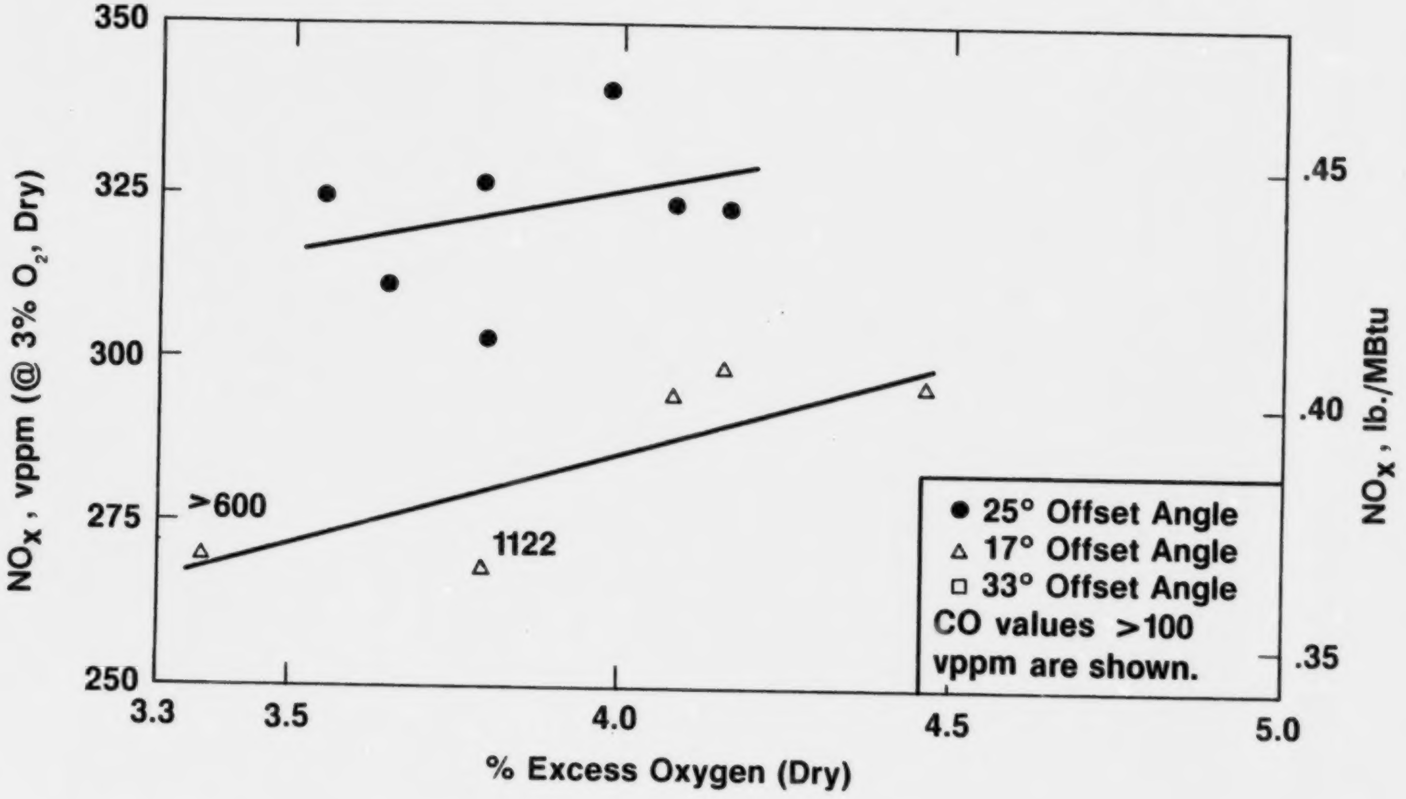

Figure D-3
Effect of Excess Oxygen and Offset Angle on NO_x Levels:
Full Load Operation Under Modification 1
with Moderate Overfire Air Staging

1084-3-338

TABLE D-4
DATA FOR FIGURE D-3
EFFECT OF EXCESS OXYGEN ON NOX LEVELS: FULL LOAD OPERATION UNDER MODIFICATION 1 WITH MODERATE OVERFIRE AIR STAGING

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT 02	NOX VPPM	CO VPPM	NOTES
17 Degree Offset Angle															
233	428	5	50	5.2	100	17	0	0	39	0	0	4.08	295	90	
234	427	5	100	5.5	100	17	0	0	36	0	0	3.37	270	>626	1
235	421	5	100	3.7	100	17	0	0	60	0	0	4.15	299	37	
236	420	5	100	5.4	100	17	0	0	35	0	0	3.79	268	1122	
251	---	5	100	4.5	100	17	0	0	65	0	0	4.46	296	38	2
25 Degree Offset Angle															
202	428	5	100	5.6	100	25	0	0	45	0	0	3.79	327	32	
203	427	5	50	5.3	100	25	0	0	47	0	0	4.08	323	34	
206	419	5	100	3.7	100	25	0	0	70	0	0	4.16	323	18	
207	424	5	100	5.2	100	25	0	0	42	0	0	3.80	303	68	
208	423	5	100	5.5	50	25	0	0	48	0	0	3.98	341	16	
209	425	5	100	5.4	50	25	0	0	44	0	0	3.55	325	66	
210	422	5	50	5.5	50	25	0	0	45	0	0	3.65	311	31	
33 DEGREE OFFSET ANGLE															3
238	417	5	50	5.2	100	33	0	0	45	0	0	4.88	337	41	3
244	411	5	100	5.4	100	33	0	0	34	0	0	4.69	290	860	3
246	411	5	100	5.3	100	33	0	0	35	0	0	4.03	256	2250	3
247	410	5	50	5.4	100	33	0	0	36	0	0	4.19	269	1299	3

Notes:

1. CO scale not properly set for one of the probe assemblies; therefore, a > symbol has been added.
2. Load data not taken, however, the load was ~415 MWe.
3. Because most of these 33 degree offset tests resulted in high CO data, they have not been included in figure D-3.

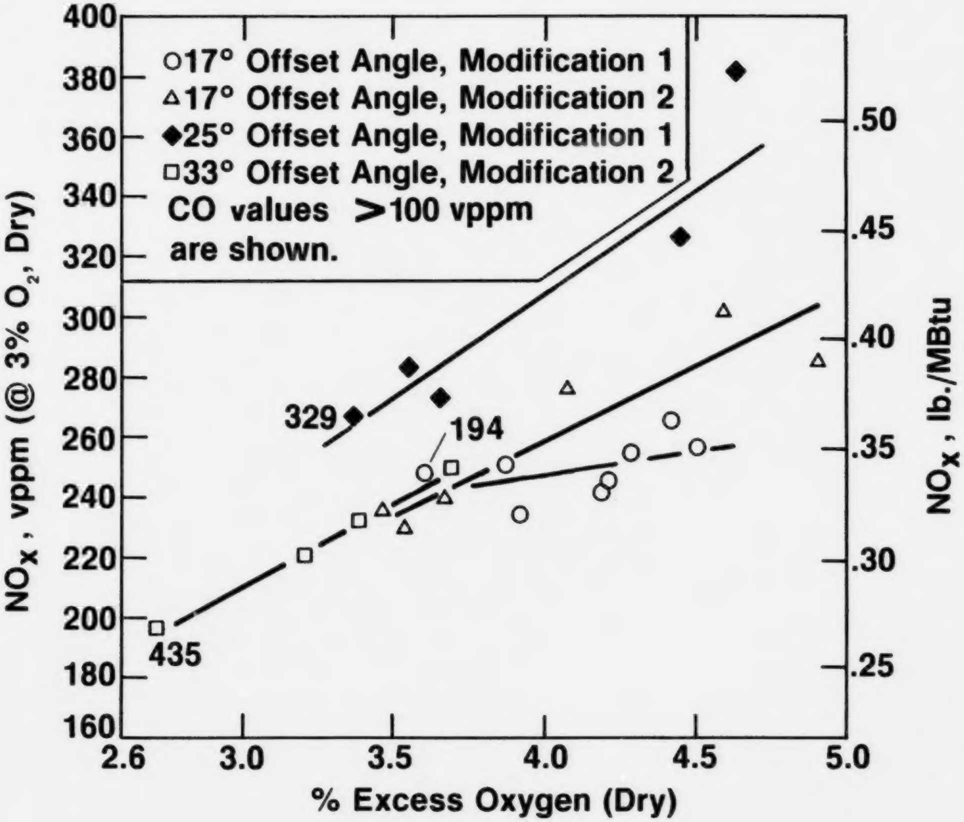

Figure D-4
Effect of Excess Oxygen on NO$_x$ Levels for
Different Offset Angles and Hardware Modifications:
Full Load Operation with Near-Maximum Overfire Air Staging

1084-3-337

TABLE D-5
DATA FOR FIGURE D-4
EFFECT OF EXCESS OXYGEN ON NOx LEVELS FOR DIFFERENT OFFSET ANGLES AND HARDWARE MODIFICATIONS: FULL LOAD OPERATION WITH DEEP OVERFIRE AIR STAGING

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM
17 Degree Offset Angle, Modification 1														
255	418	5	100	5.5	100	17	30	-15	30	0	0	3.61	247	194
261	420	5	100	5.7	100	17	30	-15	26	50	0	4.19	242	8
262	420	5	100	6.3	100	17	30	-15	26	50	0	4.21	246	28
263	426	5	100	5.8	100	17	30	-15	30	0	0	3.87	251	268
264	419	5	100	6.1	100	17	30	-15	26	0	26	3.92	235	100
265	419	5	100	6.2	100	17	30	-15	20	50	20	4.29	255	26
268	420	5	100	6.1	100	17	30	-23	30	0	30	4.42	266	29
269	420	5	100	5.9	100	17	30	-23	30	0	30	4.51	257	31
17 Degree Offset Angle, Modification 2														
311	411	5	100	5.5	100	17	30	-16	24	50	24	3.68	240	193
312	407	5	100	5.5	100	17	30	-16	20	100	20	3.54	230	136
331	427	5	100	5.5	100	17	30	-15	28	50	28	3.47	236	111
332	427	5	100	5.5	100	17	30	-15	27	50	27	4.60	302	29
333	428	5	100	9.0	100	17	30	-15	17	50	17	4.91	285	25
334	430	5	100	6.0	100	17	30	-15	26	50	26	4.08	276	43
25 Degree Offset Angle, Modification 1														
216	422	5	100	5.5	100	25	30	-15	40	0	0	3.56	284	15
219	420	5	100	5.6	100	25	30	-15	37	0	0	3.66	274	22
223	420	5	100	5.1	100	25	30	-15	39	0	0	4.46	327	15
224	420	5	100	5.2	100	25	30	-15	45	0	0	4.64	383	28
257	433	5	100	5.4	100	25	30	-13	36	0	0	3.37	269	329
33 Degree Offset Angle, Modification 2														
302	398	5	100	5.5	100	33	30	-15	20	50	20	3.69	250	62
303	399	5	100	5.5	100	33	30	-15	16	50	16	3.20	221	61
304	399	5	100	5.5	100	33	30	-15	16	50	16	3.38	233	90
313	408	5	100	5.5	100	33	30	-16	16	100	16	2.71	197	435

MW_e) are shown. From the plot, one can see that NO_x levels decreased approximately 50 vppm for both load cases. These average NO_x sensitivities (to excess oxygen levels) for Modifications 1 and 2 tests are comparable to the baseline sensitivity levels of 50 vppm and 70 vppm decreases per 1.0% excess oxygen decrease at 400 MW_e and 300 MW_e loads, respectively.

The data represented in Figures D-1 and D-2 include data where variation existed in more than one parameter. Comparatively, in Figures D-3 and D-4, the only variable was excess oxygen. This was done to demonstrate the interrelations between the various boiler operating parameters. Figure D-3 shows the full load, Modification 1 overfire air tests that were run at moderate staging conditions. These are shown for two different offset angles. At offset angles of 25° and 17°, NO_x levels decreased approximately 18 and 28 vppm, respectively, per 1% excess oxygen decrease. As shown in Table D-4, the unit was also tested at a 33° offset angle and resulted in very low NO_x values. However, because most of these 33° data also resulted in high CO values, they have not been included in Figure D-3.

In Figure D-4, the full load, overfire air tests that were run at deep staging conditions are shown for different offset angles and for different hardware modifications. NO_x levels decreased approximately 85 and 35 vppm per 1% decrease in excess oxygen for Modification 1 tests run at offset angles of 25° and 17°, respectively, while NO_x levels decreased approximately 50 and 55 vppm per 1% decrease in excess oxygen for Modification 2 tests run at offset angles of 17° and 33°, respectively. The results of these two figures clearly demonstrate the variability of the NO_x vs. excess oxygen trend, which is due to the effect of parametric interrelationships.

B. Effects of Windbox Modifications 1 and 2 and Overfire Air on NO_x Levels

The effects of Modifications 1 and 2 on NO_x levels compared to baseline conditions are shown in Figure D-5. The test data are listed in Table D-6. On the average, Modification 1 by itself did not decrease NO_x levels, whereas Modification 2 reduced NO_x levels by about 80 vppm. However, during Modification 2, only three non-overfire air tests were performed due to the large oxygen imbalance between ducts which occurred often during these Modification 2 tests.

The effect of overfire air plus Modification 1 on NO_x levels is also shown in Figure D-5. Only high level overfire air tests (overfire air dampers wide open) were performed during this phase of testing. On the average, NO_x reductions of about 140 vppm were achieved during Modification 1 when using average to moderate staging. This compares with baseline tests in which overfire air could decrease NO_x emissions by only 80 vppm. Because Modification 1 by itself did not reduce NO_x levels over baseline levels, this 60 vppm differential suggests a synergistic effect on NO_x reductions caused by Modification 1 plus overfire air.

Regarding the combined effect of Modification 2 plus overfire air on NO_x levels, this combination yielded similar or slightly greater NO_x reductions than those of Modification 1 with overfire air. These results are shown in Figures D-6 through D-8, and the data are listed in Tables D-7 through D-9, respectively. In Figure D-6, NO_x levels are shown for moderate staging conditions. On the average, Modification 2 tests yielded NO_x levels about 40 vppm lower than Modification 1. This plot also

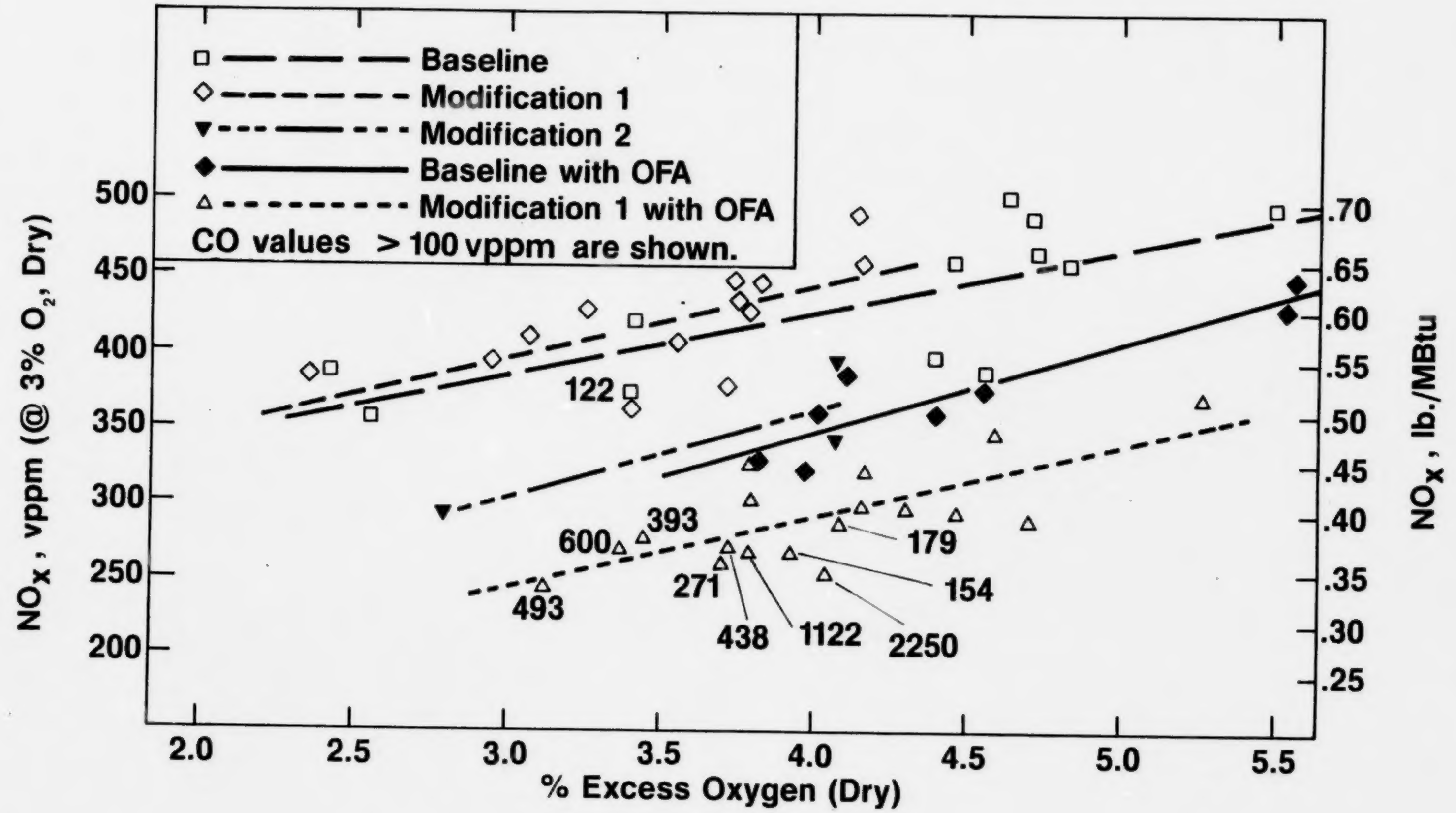

Figure D-5
Effects of Modifications 1 and 2
Plus Overfire Air on NO_x Levels

TABLE D-6 (PG 1 OF 2)
DATA FOR FIGURE D-5
EFFECTS OF MODIFICATIONS 1 AND 2 PLUS OVERFIRE AIR ON NOx LEVELS

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
Baseline (no OFA)															
14	395	5	96	5.5	0	0	0	5	21	60	21	4.70	488	62	
15	396	5	70	5.0	0	0	0	3	21	60	21	4.45	459	63	
16	394	5	50	5.1	0	0	0	7	26	60	26	4.55	387	56	
22	392	5	93	5.0	0	0	0	4	21	60	21	4.62	503	17	
23	394	5	93	5.0	0	0	0	-1	26	60	26	5.48	496	10	
24	390	5	93	3.7	0	0	0	2	0	60	0	2.56	355	16	
37	411	5	98	4.7	0	0	0	0	0	60	0	3.38	382	122	
38	417	5	50	5.0	0	0	0	0	25	60	25	3.40	374	14	
40	413	5	98	5.0	0	0	0	0	29	60	29	4.82	457	13	
41	411	5	98	5.0	0	0	0	0	20	60	20	3.41	418	14	
51	395	5	50	5.2	0	0	0	0	29	0	29	4.39	396	15	
Baseline With Overfire Air (OFAD > 0)															
8	403	5	85	4.2	100	0	0	0	0	0	0	4.10	385	33	
11	399	5	95	4.0	100	0	0	7	0	0	0	4.55	375	47	
13	401	5	95	4.5	100	0	30	6	0	0	0	3.80	327	43	
45	411	5	98	5.0	100	0	0	0	8	0	8	4.01	360	11	1
46	391	5	98	5.0	100	0	0	0	0	60	0	5.56	450	11	
47	391	5	98	5.0	100	0	0	0	18	0	18	5.53	430	14	
48	385	5	98	4.5	100	0	0	0	0	0	0	4.39	360	16	
49	389	5	98	4.5	100	0	30	0	0	0	0	3.97	323	18	
Modification 1 (no OFA)															
101	402	5	100	5.5	0	25	0	0	39	50	39	3.71	376	12	
102	399	5	100	3.7	0	25	0	-3	50	50	50	3.40	362	12	
105	406	5	100	6.0	0	25	0	-1	38	50	38	3.82	445	11	
106	406	5	100	5.0	0	33	0	1	40	0	40	3.75	434	12	
107	403	5	100	5.0	0	25	0	0	36	0	36	3.73	446	10	
111	407	5	100	3.5	0	25	0	0	48	0	48	3.07	407	12	
112	404	5	100	3.5	0	25	0	0	50	0	50	3.26	426	10	
113	405	5	100	3.5	0	25	0	0	41	0	41	2.36	383	12	
114	404	5	100	3.5	0	25	0	1	55	10	0	3.78	426	11	
118	400	5	100	5.5	0	25	0	0	50	0	0	3.55	406	11	
122	393	5	20	4.0	0	33	0	0	100	0	0	3.82	355	12	2
201	418	5	100	5.2	0	25	0	0	70	0	0	4.15	458	15	
242	425	5	100	5.4	0	33	0	0	48	50	48	4.13	489	12	

TABLE D-6 (PG 2 OF 2)
DATA FOR FIGURE D-5
EFFECTS OF MODIFICATIONS 1 AND 2 PLUS OVERFIRE AIR ON NOx LEVELS

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
Modification 1 With Overfire Air (OFAD > 0)															
116	401	5	100	5.5	100	25	0	0	38	10	0	5.26	373	12	
117	406	5	100	5.5	100	25	0	1	30	10	0	3.72	272	36	
202	428	5	100	5.6	100	25	0	0	45	0	0	3.79	327	32	
203	427	5	50	5.3	100	25	0	0	47	0	0	4.08	323	34	
206	419	5	100	3.7	100	25	0	0	70	0	0	4.16	323	18	
207	424	5	100	5.2	100	25	0	0	42	0	0	3.80	303	68	
215	424	5	100	5.5	100	25	30	0	40	0	0	3.13	246	493	
217	420	5	100	5.5	100	25	30	0	37	0	0	3.44	277	393	
234	427	5	100	5.5	100	17	0	0	36	0	0	3.37	270	>626	3
235	421	5	100	3.7	100	17	0	0	60	0	0	4.15	299	37	
236	420	5	100	5.4	100	17	0	0	35	0	0	3.79	268	1122	
237	420	5	100	5.4	100	33	0	0	44	0	0	4.58	346	45	
245	411	5	100	5.5	100	33	0	0	29	100	0	3.70	261	271	
246	411	5	100	5.3	100	33	0	0	35	0	0	4.03	256	2250	
254	418	5	100	5.5	100	17	30	0	35	0	0	3.92	269	154	
256	423	5	100	5.6	100	17	30	0	43	0	0	4.30	299	43	
258	432	5	100	5.5	100	25	30	0	35	0	0	3.70	263	438	
259	434	5	100	6.0	100	25	30	0	35	0	0	4.08	287	179	
260	425	5	100	6.0	100	17	30	0	30	50	0	4.07	266	70	
Modification 2 (no OFA)															
309	425	5	100	5.5	0	17	0	5	45	50	45	2.82	291	85	
338	421	5	100	5.5	0	5	0	0	44	50	44	4.03	340	56	
339	420	5	100	5.5	0	25	0	0	48	50	48	4.06	385	56	

Notes:

1. Left front OFAT at +10 degrees.
2. Top FAD open 100%.
3. CO scale not properly set for one of the probe assemblies; therefore, a > symbol has been added.

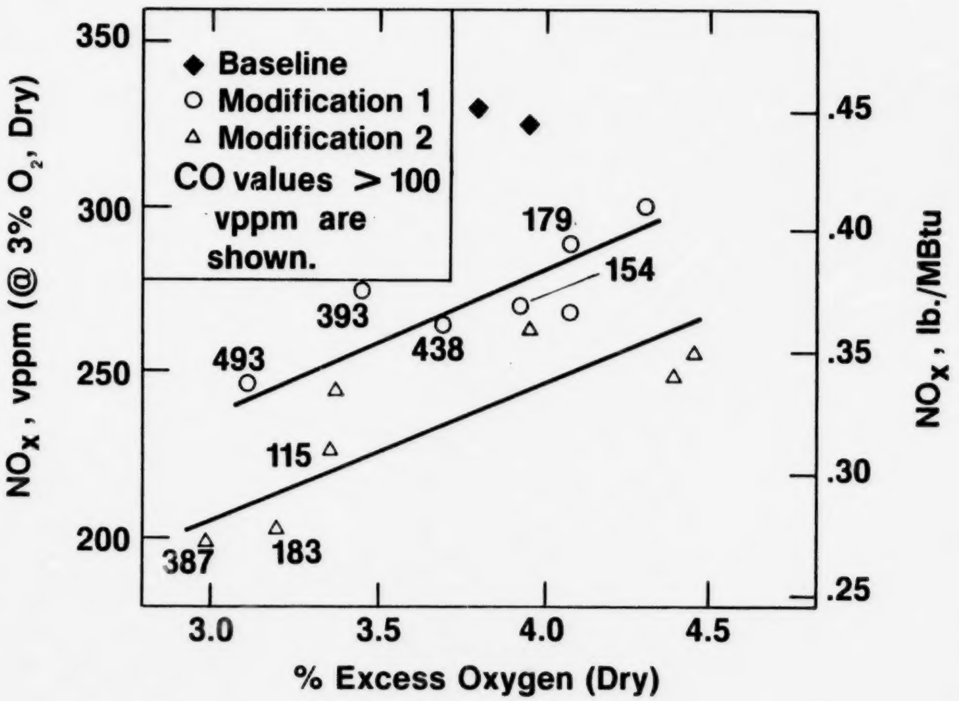

Figure D-6
Effects of Modifications 1 and 2 and Excess Oxygen
on NO_x Levels for Full Load Operation
Under Moderate Staging Conditions

TABLE D-7
DATA FOR FIGURE D-6
EFFECTS OF MODIFICATIONS 1 AND 2 AND EXCESS OXYGEN ON NOx LEVELS FOR FULL LOAD OPERATION UNDER MODERATE STAGING CONDITIONS

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
							Baseline								
13	401	5	95	4.5	0	0	30	6	0	0	0	3.80	327	43	
49	389	5	98	4.5	100	0	30	0	0	0	0	3.97	323	18	
							Modification 1								
215	424	5	100	5.5	100	25	30	0	40	0	0	3.13	246	493	
217	420	5	100	5.5	100	25	30	0	37	0	0	3.44	277	393	
254	418	5	100	5.5	100	17	30	0	35	0	0	3.92	269	154	
256	423	5	100	5.6	100	17	30	0	43	0	0	4.30	299	43	
258	432	5	100	5.5	100	25	30	0	35	0	0	3.70	263	438	
259	434	5	100	6.0	100	25	30	0	35	0	0	4.08	287	179	
260	425	5	100	6.0	100	17	30	0	30	50	0	4.07	266	70	
							Modification 2								
301	402	5	100	5.5	100	33	30	-4	23	50	23	3.96	264	43	
305	398	5	100	5.5	100	33	30	0	20	50	20	3.38	245	115	1
306	400	5	100	5.5	100	33	30	0	30	50	30	4.45	255	44	
310	412	5	100	5.5	100	17	30	-5	20	50	20	2.99	201	387	
337	422	5	100	5.5	100	5	15	0	28	50	28	4.39	250	81	
345	419	5	100	5.5	100	25	15	0	20	50	20	3.37	227	183	2

Notes:

1. High oxygen imbalance.
2. Top auxiliary air compartments (AUX 1) were 100% open, and at an 8 degree offset angle.

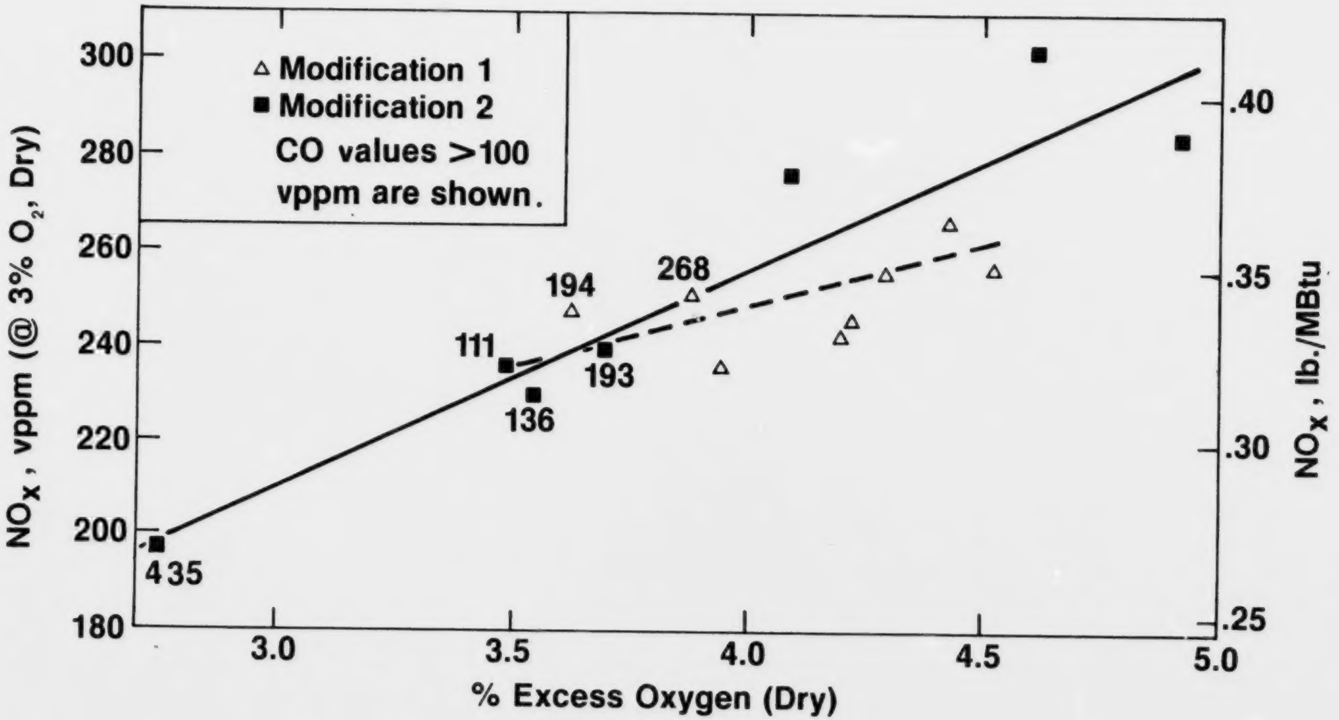

Figure D-7
Effects of Modifications 1 and 2 and Excess Oxygen on NO_X Levels for Full Load Operation Under Deep Staging Conditions

TABLE D-8
DATA FOR FIGURE D-7
EFFECTS OF MODIFICATIONS 1 AND 2 AND EXCESS OXYGEN ON NOx LEVELS FOR FULL LOAD OPERATION UNDER DEEP STAGING CONDITIONS

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM
							Modification 1							
255	418	5	100	5.5	100	17	30	-15	30	0	0	3.61	247	194
261	420	5	100	5.7	100	17	30	-15	26	50	0	4.19	242	8
262	420	6	100	6.3	100	17	30	-15	26	50	0	4.21	246	28
263	426	5	100	5.8	100	17	30	-15	30	0	0	3.87	251	268
264	419	5	100	6.1	100	17	30	-15	26	0	26	3.92	235	100
265	419	5	100	6.2	100	17	30	-15	20	50	20	4.29	255	26
268	420	5	100	6.1	100	17	30	-23	30	0	30	4.42	266	29
269	420	5	100	5.9	100	17	30	-23	30	0	30	4.51	257	31
							Modification 2							
311	411	5	100	5.5	100	17	30	-16	24	50	24	3.68	240	193
312	407	5	100	5.5	100	17	30	-16	20	100	20	3.54	230	136
313	408	5	100	5.5	100	33	30	-16	16	100	16	2.71	197	435
331	427	5	100	5.5	100	17	30	-15	28	50	28	3.47	236	111
332	427	5	100	5.5	100	17	30	-15	27	50	27	4.60	302	29
333	428	5	100	9.0	100	17	30	-15	17	50	17	4.91	285	25
334	430	5	100	6.0	100	17	30	-15	26	50	26	4.08	276	43

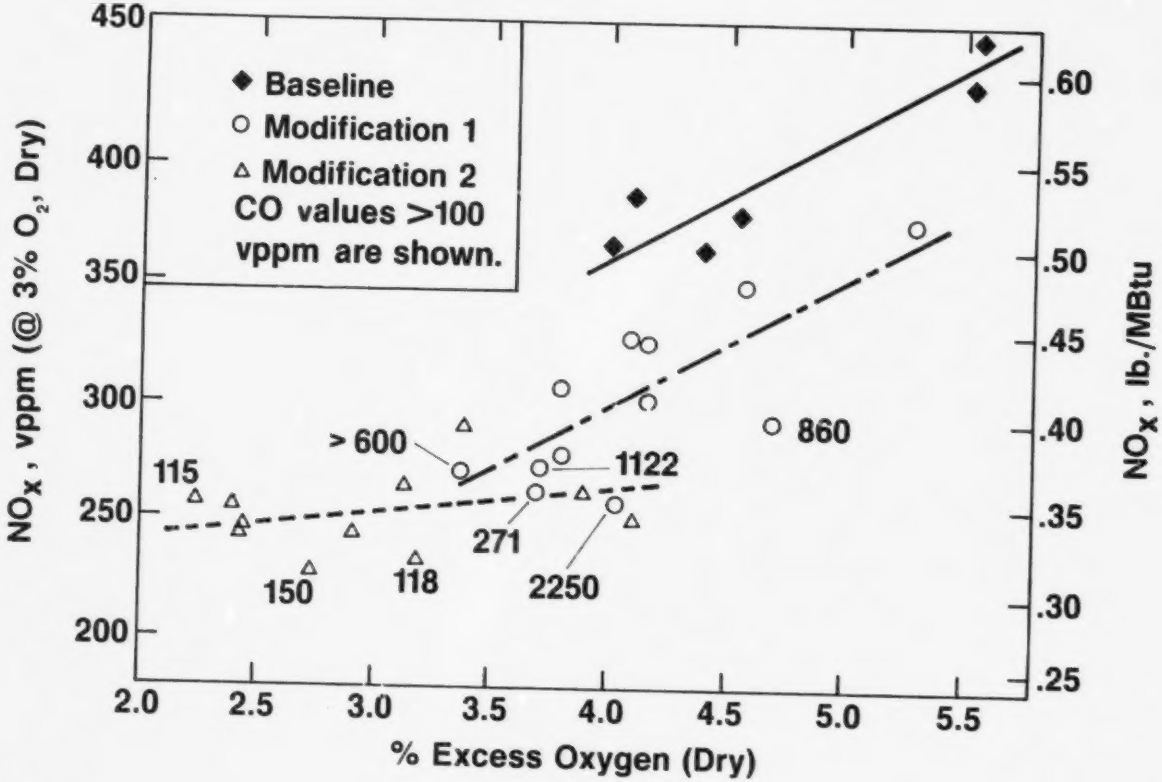

Figure D-8
Effects of Modifications 1 and 2 and Excess Oxygen on NO_x Levels for Full Load Operation Under Average Staging Conditions with Fuel Air Dampers Open ≥80%

TABLE D-9
DATA FOR FIGURE D-8
EFFECTS OF MODIFICATIONS 1 AND 2 AND EXCESS OXYGEN ON NOx LEVELS FOR FULL LOAD OPERATION UNDER AVERAGE STAGING CONDITIONS

TEST NO	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT 02	NOX VPPM	CO VPPM	NOTES
Baseline															
8	403	5	85	4.2	100	0	0	0	0	0	0	4.10	385	33	
11	399	5	95	4.0	100	0	0	7	0	0	0	4.55	375	47	
45	411	5	98	5.0	100	0	0	0	8	0	8	4.01	360	11	1
46	391	5	98	5.0	100	0	0	0	0	60	0	5.56	450	11	
47	391	5	98	5.0	100	0	0	0	18	0	18	5.53	430	14	
48	385	5	98	4.5	100	0	0	0	0	0	0	4.39	360	16	
Modification 1															
202	428	5	100	5.6	100	25	0	0	45	0	0	3.79	327	32	
203	427	5	50	5.3	100	25	0	0	47	0	0	4.08	323	34	
206	419	5	100	3.7	100	25	0	0	70	0	0	4.16	323	18	
207	424	5	100	5.2	100	25	0	0	42	0	0	3.80	303	68	
116	401	5	100	5.5	100	25	0	0	38	10	0	5.26	373	12	
117	406	5	100	5.5	100	25	0	1	30	10	0	3.72	272	36	
234	427	5	100	5.5	100	17	0	0	36	0	0	3.37	270	>626	2
235	421	5	100	3.7	100	17	0	0	60	0	0	4.15	299	37	
236	420	5	100	5.4	100	17	0	0	35	0	0	3.79	268	1122	
237	420	5	100	5.4	100	33	0	0	44	0	0	4.58	346	45	
244	411	5	100	5.4	100	33	0	0	34	0	0	4.69	290	860	
245	411	5	100	5.5	100	33	0	0	29	100	0	3.70	261	271	
246	411	5	100	5.3	100	33	0	0	35	0	0	4.03	256	2250	
Modification 2															
352	428	5	100	5.5	100	17	0	-5	20	50	20	3.20	233	118	3
353	404	5	100	5.5	100	17	0	-3	20	50	20	4.11	250	61	4
315	416	5	100	5.5	100	17	0	0	25	100	25	3.39	288	40	
316	416	5	100	5.5	100	17	0	0	20	100	20	2.26	258	115	
317	412	5	100	5.5	100	33	0	0	14	100	14	2.41	254	56	
318	412	5	100	5.5	100	33	0	0	14	100	14	2.46	248	95	
319	416	5	100	5.5	100	33	0	0	22	25	22	2.43	248	55	
342	417	5	100	5.5	100	25	0	0	24	50	24	3.12	265	58	
343	419	5	100	5.5	100	25	0	0	14	50	14	2.75	229	150	5
344	414	5	100	5.5	100	25	0	0	12	50	12	2.92	244	73	3

Notes:
1. Left front OFAT at +10 degrees.
2. CO scale not properly set for one of the probe assemblies; therefore, a ">" symbol has been added.
3. Top auxiliary air compartments (AUX 1) were 100% open, and at an 8 degree offset angle.
4. Top auxiliary air compartments (AUX 1) were on automatic, and at an 8 degree offset angle.
5. Top auxiliary air compartments (AUX 1) were 100% open.

shows NO_x reductions of about 40 vppm for Modification 1 relative to baseline levels which, as previously discussed, can be attributed to synergistic effects. In Figure D-7, NO_x levels are shown for deep staging conditions. Results indicate very similar trends for both Modifications 1 and 2. This suggests that the large NO_x reductions obtained with deep staging overshadow the effects of the Modification 2 hardware changes.

In Figure D-8, NO_x levels are shown for an average degree of staging. Unfortunately, it is difficult to quantitatively compare the differences in NO_x levels for Modifications 1 and 2 because the tests for each modification phase were focused in different excess oxygen ranges. However, two observations can be made from this plot. First, it appears that for low oxygen levels in Modification 2, the NO_x levels are not very sensitive to excess oxygen, but rather, began to plateau towards a constant level. Second, on the average, the Modification 1 results showed NO_x levels of about 50 vppm lower than baseline levels. Again, this may be attributed to the Modification 1 plus overfire air synergism.

The above results show that the use of overfire air in Modification 1 creates a synergistic effect which yields NO_x reductions that are about 50 vppm greater than were seen during baseline overfire air testing. Complementary to this, in some cases, the use of Modification 2 with overfire air yields markedly lower NO_x levels than Modification 1 plus overfire air. However, at other conditions, both modifications yield similar levels. These observations clearly demonstrate the existence of strong parametric interrelations in Hunter Unit No. 2.

C. Factors Which Affect Boiler Operability and NO_x Reduction Potentials

The hardware and operational modifications conducted in the post-modification phases of testing greatly increased the complexity of the boiler aerodynamics at the Hunter Unit No. 2 Unit. This increased complexity affected boiler operating flexibility and stability, which in turn limited the NO_x reduction potential at certain operating conditions. NO_x reductions and boiler operating flexibility were limited by automatic burner tilt controls, flue gas excess oxygen imbalances (between the two economizer flue gas exhaust ducts), and high CO levels. These limits were evaluated.

1. Automatic Burner Tilt Positions--(with clean boiler walls)

Normal full load burner tilt levels are automatically controlled to maintain design reheat outlet steam temperatures. During short term testing, it is possible to manually override the automatic controls, but during long term operation they must be kept operational to maintain smooth boiler performance. In baseline tests conducted with clean boiler walls (after sootblowing) and without overfire air, the burner tilts adjusted automatically to approximately a horizontal position. With the hardware and operational changes instituted during Modification 1 testing (including overfire air usage), the burner tilts automatically lowered to approximately -10° to -15°. This reduction was mainly due to effects of hardware changes, and to a reduction of the excess oxygen set point (i.e., to 3% O_2 [in whichever of the two boiler outlet ducts had the lowest O_2 reading]). This reduction was also due, slightly, to the use of overfire air. This automatic reduction in burner tilts allowed fairly stable boiler operation at moderate and deep staging (w/OFA) conditions. Modification 2, on the other hand, caused the burner tilts to automatically raise back up to the horizontal position. As such, deep and moderate staging frequently created unstable conditions, such as steam tube temperature and oxygen imbalances, and high CO levels.

2. Oxygen Imbalance--

One of the limitations to achieving extremely low-NO_x levels by running at very low oxygen levels at Hunter No. 2, is an oxygen imbalance that frequently occurred between the two furnace exhaust (flue gas) ducts. The boiler's air flow controller ensures that neither duct has an oxygen concentration below the set point (e.g., 3% O_2). Therefore, as the oxygen imbalance increases, so does the average oxygen level which, in turn causes higher NO_x levels. In addition to affecting the NO_x reduction capability of the boiler, the oxygen imbalance also affects the boiler by decreasing its efficiency. This occurs mainly through increased dry gas losses, increased use of cooling sprays, and increased variation in steam tube temperatures. This complicates boiler operation and makes it difficult to control.

The presence of an oxygen imbalance is not unique to Hunter Unit No. 2, but has also been observed at other tangentially-fired units. At Hunter Unit No. 2, the imbalance existed during the baseline testing and appears to have increased as a result of the windbox modifications. Modification 1 increased the imbalance slightly, however, deep staging was still possible in many cases. Modification 2 increased the imbalance further, such that under many sets of conditions, deep and moderate staging was not possible. Modification 3 reduced the degree of imbalance created by Modification 2 somewhat and thereby returned a degree of stability to the boiler.

Many theories have been developed and tested regarding the cause of the oxygen imbalance, but none have provided conclusive results. Most probably, the oxygen imbalance is due to the complex aerodynamics in the boiler, and is probably caused by insufficient mixing of the fuel and combustion air, especially in the highly staged (air) low-NO_x mode.

Some observations associated with the oxygen imbalance are listed below:

- Even though the oxygen imbalance was measured in the economizer outlet ducts, the imbalance occurred in the furnace section. This was suggested by the fact that during several tests with a substantial oxygen imbalance, the outlet ducts with the high and low respective O_2 readings reversed themselves in the middle of a test.

- At certain times, a given set of boiler operating conditions yielded a large oxygen imbalance, whereas at other times, very similar operating conditions did not. No explanation was apparent.

- Many scheduled characterization tests were not run at the prescribed set of operating conditions due to a large oxygen imbalance which occurred during the test set-up period. For such aborted tests, the boiler operating conditions were not always recorded.

- Many times, tests were scheduled at conditions which the control board operators knew would cause a large oxygen imbalance. In these cases, the operators would manually override the automatic controls to reduce the imbalance. Such measures included, for example, setting the burner tilts on manual control, using the soot blowers ("retracts"), increasing the amount of overfire air, and using reheat or superheat sprays. However, when oxygen imbalance control measures were employed, these measures were usually not recorded.

3. Carbon Monoxide Levels--

In typical combustion operations, there is a characteristic carbon monoxide (CO) versus excess oxygen profile. As O_2 levels are decreased, CO levels remain relatively constant until a certain O_2 threshhold is reached. Then, CO levels begin to rise sharply as excess oxygen levels are further reduced. Such profiles were apparent for several of the Modification 1 tests. As an example, these profiles are shown in Figures D-9 and D-10, and the data listed in Tables D-10 and D-11, respectively. In Figure D-9, the sensitivity of CO levels to offset angle is shown for average staging (via offset angle) conditions. A 25° offset angle demonstrated the greatest ability to maintain low CO levels at low excess oxygen levels. This was followed by a 17° offset angle and then a 33° offset angle. Figure D-10 shows the sensitivity of CO levels to both offset angle and degree of staging. At deep staging conditions, the same offset angle progression as in Figure D-9 applies. However, the opposite effect was seen with moderate staging conditions.

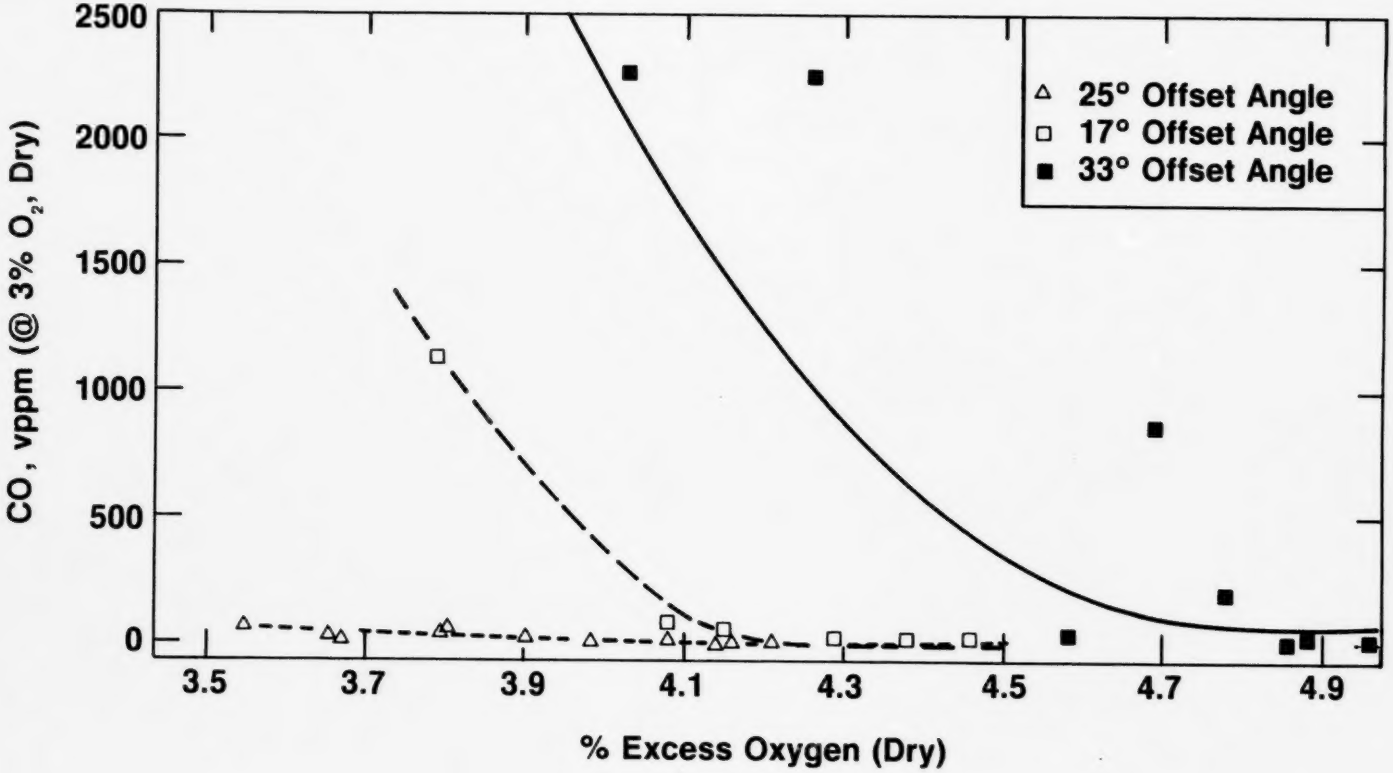

Figure D-9
Effects of Excess Oxygen and
Offset Angles on CO Levels
(Average Staging, Modification 1 Results)

1084-3-349

TABLE D-10
DATA FOR FIGURE D-9
EFFECTS OF EXCESS OXYGEN AND OFFSET ANGLES ON CO LEVELS
(AVERAGE STAGING, MODIFICATION 1 RESULTS)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
17 Degree Offset Angle															
231	417	5	10	5.3	100	17	0	0	52	0	0	4.38	287	31	
232	422	5	20	5.4	100	17	0	0	46	0	0	4.29	296	20	
233	428	5	50	5.2	100	17	0	0	39	0	0	4.08	295	90	
235	421	5	100	3.7	100	17	0	0	60	0	0	4.15	299	37	
236	420	5	100	5.4	100	17	0	0	35	0	0	3.79	268	1122	
251	---	5	100	4.5	100	17	0	0	65	0	0	4.46	296	38	1
25 Degree Offset Angle															
202	428	5	100	5.6	100	25	0	0	45	0	0	3.79	327	32	
203	427	5	50	5.3	100	25	0	0	47	0	0	4.08	323	34	
204	418	5	20	5.6	100	25	0	0	49	0	0	4.14	309	14	
205	414	5	10	5.5	100	25	0	0	56	0	0	4.21	296	11	
206	419	5	100	3.7	100	25	0	0	70	0	0	4.16	323	18	
207	424	5	100	5.2	100	25	0	0	42	0	0	3.80	303	68	
208	423	5	100	5.5	50	25	0	0	48	0	0	3.98	341	16	
209	425	5	100	5.4	50	25	0	0	44	0	0	3.55	325	66	
210	422	5	50	5.5	50	25	0	0	45	0	0	3.65	311	31	
211	420	5	20	5.4	50	25	0	0	51	0	0	3.67	307	17	
212	414	5	10	5.3	50	25	0	0	60	0	0	3.90	300	22	
33 Degree Offset Angle															
237	420	5	100	5.4	100	33	0	0	44	0	0	4.58	346	45	
238	417	5	50	5.2	100	33	0	0	45	0	0	4.88	337	41	
239	415	5	20	5.3	100	33	0	0	50	0	0	4.96	334	23	
240	415	5	10	5.4	100	33	0	0	56	0	0	4.86	347	16	
244	411	5	100	5.4	100	33	0	0	34	0	0	4.69	290	860	
246	411	5	100	5.3	100	33	0	0	35	0	0	4.03	256	2250	
247	410	5	50	5.4	100	33	0	0	36	0	0	4.19	269	1299	
248	412	5	20	5.4	100	33	0	0	40	0	0	4.30	266	272	
249	410	5	10	5.2	100	33	0	0	47	0	0	4.78	260	217	

Note:

1. Load data not taken, however, the load was ~415 MWe.

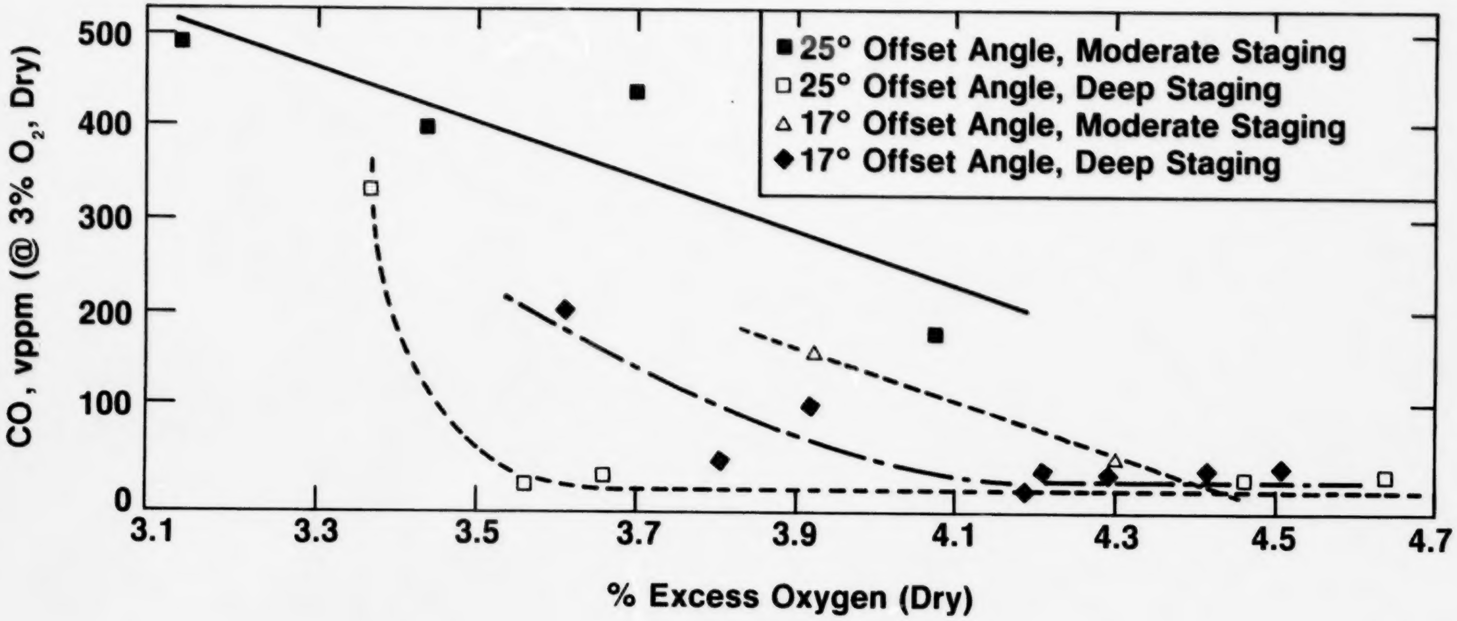

Figure D-10
Effects of Excess Oxygen, Offset Angle and
Degree of Staging on CO Levels
(Modification 1 Results)

1084-3-348

TABLE D*11
DATA FOR FIGURE D-10
EFFECTS OF EXCESS OXYGEN, OFFSET ANGLE AND DEGREE OF STAGING ON CO LEVELS

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT 02	NOX VPPM	CO VPPM
25 Degree Offset Angle, Moderate Staging														
215	424	5	100	5.5	100	25	30	0	40	0	0	3.13	246	493
217	420	5	100	5.5	100	25	30	0	37	0	0	3.44	277	393
258	432	5	100	5.5	100	25	30	0	35	0	0	3.70	263	438
259	434	5	100	6.0	100	25	30	0	35	0	0	4.08	287	179
25 Degree Offset Angle, Deep Staging														
216	422	5	100	5.5	100	25	30	-15	40	0	0	3.56	284	15
219	420	5	100	5.6	100	25	30	-15	37	0	0	3.66	274	22
223	420	5	100	5.1	100	25	30	-15	39	0	0	4.46	327	15
224	420	5	100	5.2	100	25	30	-15	45	0	0	4.64	383	28
257	433	5	100	5.4	100	25	30	-13	36	0	0	3.37	269	329
17 Degree Offset Angle, Moderate Staging														
254	418	5	100	5.5	100	17	30	0	35	0	0	3.92	269	154
256	423	5	100	5.6	100	17	30	0	43	0	0	4.30	299	43
260	425	5	100	6.0	100	17	30	0	30	50	0	4.07	266	70
17 Degree Offset Angle, Deep Staging														
255	418	5	100	5.5	100	17	30	-15	30	0	0	3.61	247	194
261	420	5	100	5.7	100	17	30	-15	26	50	0	4.19	242	8
262	420	5	100	6.3	100	17	30	-15	26	50	0	4.21	246	28
263	426	5	100	5.8	100	17	30	-15	30	0	0	3.87	251	268
264	419	5	100	6.1	100	17	30	-15	26	0	26	3.92	235	100
265	419	5	100	6.2	100	17	30	-15	20	50	20	4.29	255	26
268	420	5	100	6.1	100	17	30	-23	30	0	30	4.42	266	29
269	420	5	100	5.9	100	17	30	-23	30	0	30	4.51	257	31

The cases presented in Figures D-9 and D-10 were among the few in which the characteristic CO versus excess oxygen curves were clearly demonstrated. This is because with the complex boiler aerodynamics, slight changes in certain parameters would often totally modify both the CO versus excess O_2 profiles, and the relative parametric relationships (e.g. as shown above for different offset angles).

As discussed in Part A, Section IV, CO levels are affected by localized oxygen levels. Therefore, as testing progressed, it became more apparent that high CO levels were not only tied into an inter-duct oxygen imbalance, but they were also tied into an intra-duct oxygen imbalance. High CO levels usually appeared when a single probe assembly (for gas sampling) yielded an excess oxygen level of <2.5%. Also, there were tests where very high CO levels resulted, even though each probe assembly experienced oxygen levels of >3.0%. As discussed in Part A, Section IV, this occurred in tests conducted during marginal boiler stability, where many CO spikes (burner flickers) were observed. As explained earlier, because of the research nature of this project, it was possible to explore the effect of boiler controls outside the normal operating range. In doing so, the regions of instability were more clearly established. Because Hunter No. 2 was often tested under such conditions, there was often much variation in CO results even at comparable conditions.

Due to complex boiler aerodynamics, it was not possible to predict which operating conditions would yield high CO levels. However, some general conditions which usually caused high average CO levels included:

- low excess oxygen levels (<3.0%, average),

- fairly low excess oxygen levels (<3.5%, average), plus a substantial oxygen imbalance (>1.0% O_2 differential between ducts),
- Modification 2 tests conducted without using overfire air.

D. Effect of LNCFS Offset Angle on NO_x Levels

The effect of the LNCFS offset angle (defined in Part A, Section IV) on NO_x levels for Modification 1 tests is shown in Figures D-11 and D-12. The data for these figures are listed in Tables D-12 and D-13, respectively. Figure D-11 shows that for average staging levels, the 17° and 25° offset angles had comparable sensitivities of NO_x to excess oxygen (i.e., similar slopes). However, the 17° offset angle yielded NO_x levels that were about 40 vppm lower. Comparatively, the 33° offset angle tests proved to be more sensitive to excess oxygen levels, and thus, at low excess oxygen levels (i.e., <4.2%) they yielded lower NO_x levels than the 17° offset angle tests (15 vppm lower at 4.0% excess oxygen). In Figure D-12, at deep staging conditions, a 17° offset angle again yielded lower NO_x levels than a 25° offset angle by about 65 vppm (at 4.0% excess oxygen). Deep staging tests at a 33° offset angle were not conducted during Modification 1.

In the tests described above, it must be pointed out that most of the 33° offset angle tests yielded high CO levels ($\geq$100 vppm). Also several of the 17° offset angle tests yielded high CO levels (usually when the average excess oxygen levels were below 4.0%), and the 25° offset angle tests experienced high CO levels only when at low excess oxygen levels (<3.4%).

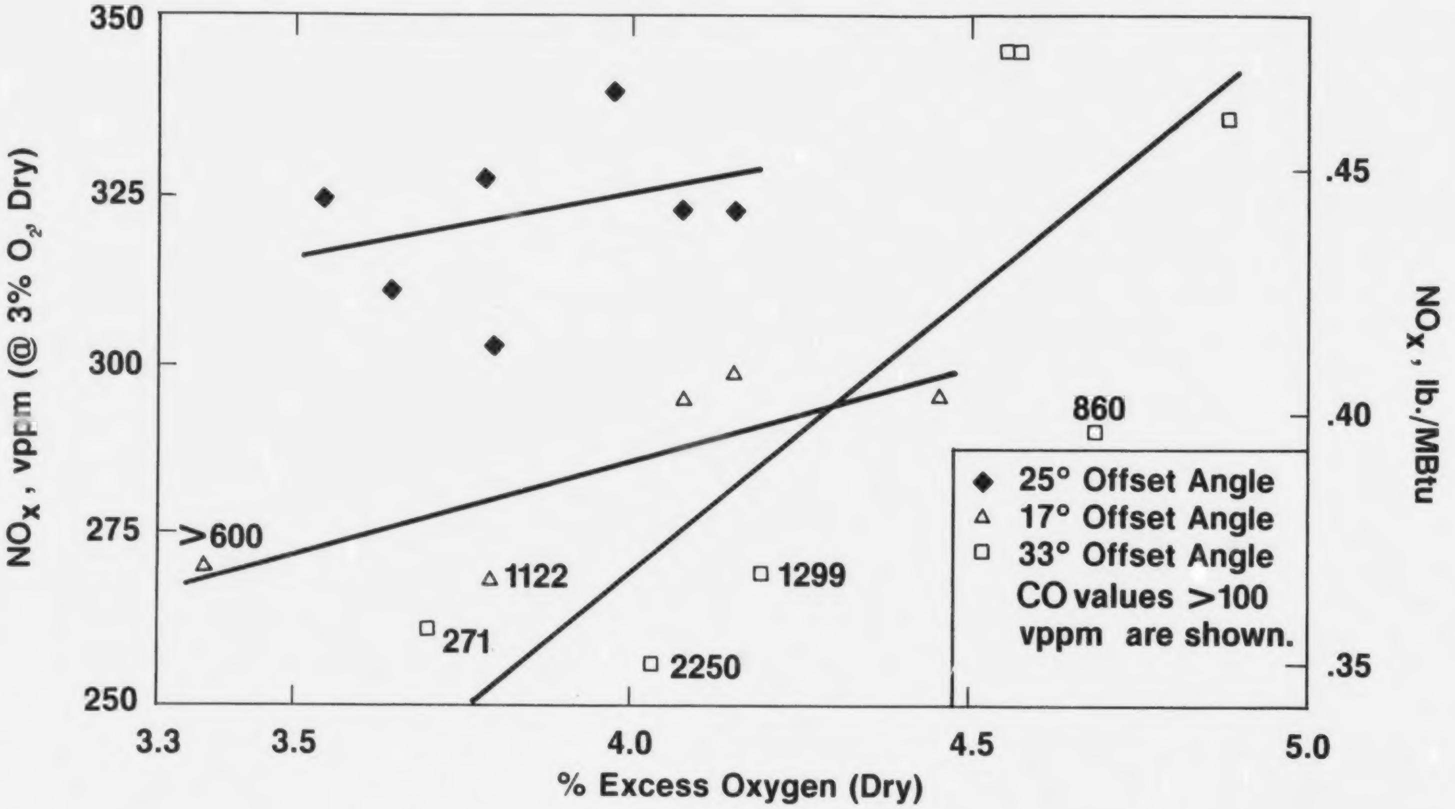

Figure D-11
Effect of LNCFS Offset Angle on NO_x Levels
(Modification 1, Average Staging Conditions)

1084-3-353

TABLE D-12
DATA FOR FIGURE D-11
EFFECT OF LNCFS OFFSET ANGLE ON NOx LEVELS
(MODIFICATION 1, AVERAGE STAGING CONDITIONS)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
17 Degree Offset Angle															
233	428	5	50	5.2	100	17	0	0	39	0	0	4.08	295	90	
234	427	5	100	5.5	100	17	0	0	36	0	0	3.37	270	>626	1
235	421	5	100	3.7	100	17	0	0	60	0	0	4.15	299	37	
236	420	5	100	5.4	100	17	0	0	35	0	0	3.79	268	1122	
251	---	5	100	4.5	100	17	0	0	65	0	0	4.46	296	38	2
25 Degree Offset Angle															
202	428	5	100	5.6	100	25	0	0	45	0	0	3.79	327	32	
203	427	5	50	5.3	100	25	0	0	47	0	0	4.08	323	34	
206	419	5	100	3.7	100	25	0	0	70	0	0	4.16	323	18	
207	424	5	100	5.2	100	25	0	0	42	0	0	3.80	303	68	
208	423	5	100	5.5	50	25	0	0	48	0	0	3.98	341	16	
209	425	5	100	5.4	50	25	0	0	44	0	0	3.55	325	66	
210	422	5	50	5.5	50	25	0	0	45	0	0	3.65	311	31	
33 Degree Offset Angle															
237	420	5	100	5.4	100	33	0	0	44	0	0	4.58	346	45	
238	417	5	50	5.2	100	33	0	0	45	0	0	4.88	337	41	
241	425	5	10	5.3	100	33	0	0	40	50	40	4.56	346	15	
244	411	5	100	5.4	100	33	0	0	34	0	0	4.69	290	860	
245	411	5	100	5.5	100	33	0	0	29	100	0	3.70	261	271	
246	411	5	100	5.3	100	33	0	0	35	0	0	4.03	256	2250	
247	410	5	50	5.4	100	33	0	0	36	0	0	4.19	269	1299	

Notes:

1. CO scale not properly set for one of the probe assemblies; therefore, a > symbol has been added.
2. Load data not taken, however, the load was ~415 MWe.

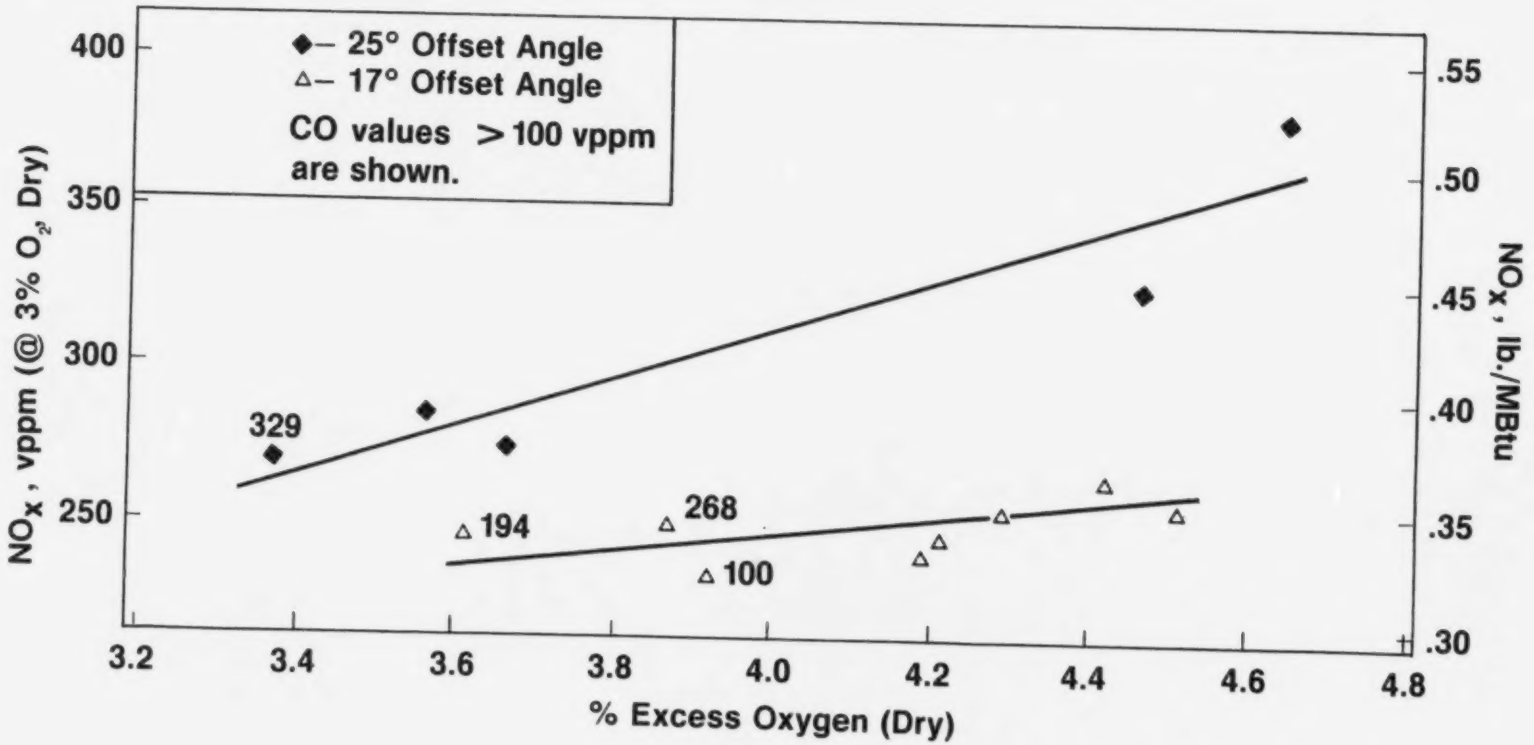

Figure D-12
Effect of LNCFS Offset Angle on NO_x Levels
(Deep Staging, Modification 1 Testing)

1084-3-356

TABLE D-13
DATA FOR FIGURE D-12
EFFECT OF LNCFS OFFSET ANGLE ON NOx LEVELS
(DEEP STAGING, MODIFICATION 1 TESTING)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM
						25 Degree Offset Angle								
216	422	5	100	5.5	100	25	30	-15	40	0	0	3.56	284	15
219	420	5	100	5.6	100	25	30	-15	37	0	0	3.66	274	22
223	420	5	100	5.1	100	25	30	-15	39	0	0	4.46	327	15
224	420	5	100	5.2	100	25	30	-15	45	0	0	4.64	383	28
257	433	5	100	5.4	100	25	30	-13	36	0	0	3.37	269	329
						17 Degree Offset Angle								
255	418	5	100	5.5	100	17	30	-15	30	0	0	3.61	247	194
261	420	5	100	5.7	100	17	30	-15	26	50	0	4.19	242	8
262	420	5	100	6.3	100	17	30	-15	26	50	0	4.21	246	28
263	426	5	100	5.8	100	17	30	-15	30	0	0	3.87	251	268
264	419	5	100	6.1	100	17	30	-15	26	0	26	3.92	235	100
265	419	5	100	6.2	100	17	30	-15	20	50	20	4.29	255	26
268	420	5	100	6.1	100	17	30	-23	30	0	30	4.42	266	29
269	420	5	100	5.9	100	17	30	-23	30	0	30	4.51	257	31

LNCFS offset angle effects on NO_x levels for Modification 2 are shown in Figure D-13. The data are listed in Table D-14. This plot shows the results of deep staging tests which were run at both 17° and 33° offset angles. Also shown for comparative purposes, are the Modification 1 data at 25° and 17° offset angles from Figure D-11. (Note: 25° offset angle Modification 2 tests were run at slightly less than full load. This was later shown to have a significant effect on NO_x levels and thus, negated their use in this analysis). On the average the 17° and 33° offset angle tests of Modification 2 yielded similar NO_x levels. Compared to the Modification 1 test results, these levels were higher than the 17° offset angle tests, but lower than the 25° offset angle tests. Concerning CO levels, most of the 17° offset angle Modification 2 tests yielded high CO levels at excess oxygen levels of <4.0%. This is similar to the Modification 1 tests. However, most of the Modification 2 deep staging tests that were run at a 33° offset angle yielded low CO levels. (The only high CO level came from a test that was run at <2.8% excess oxygen.) This can be contrasted to the high CO results that were seen in the average staging tests where a 33° offset angle was used in Modification 1.

In addition to the results just presented, other 33° offset angle Modification 2 tests were conducted. These also yielded low CO levels for average to moderate staging conditions. This implies that the use of a 33° offset angle with Modification 2 may be acceptable. However, to put the 33° offset angle operation into proper perspective, one must consider the following. As previously mentioned, Modification 2 altered the boiler's heat transfer pattern such that under normal long-term operation, moderate and deep staging were often not possible. Also, while many short term 33° offset angle tests yielded low NO_x and low CO levels, a more extensive observation of the

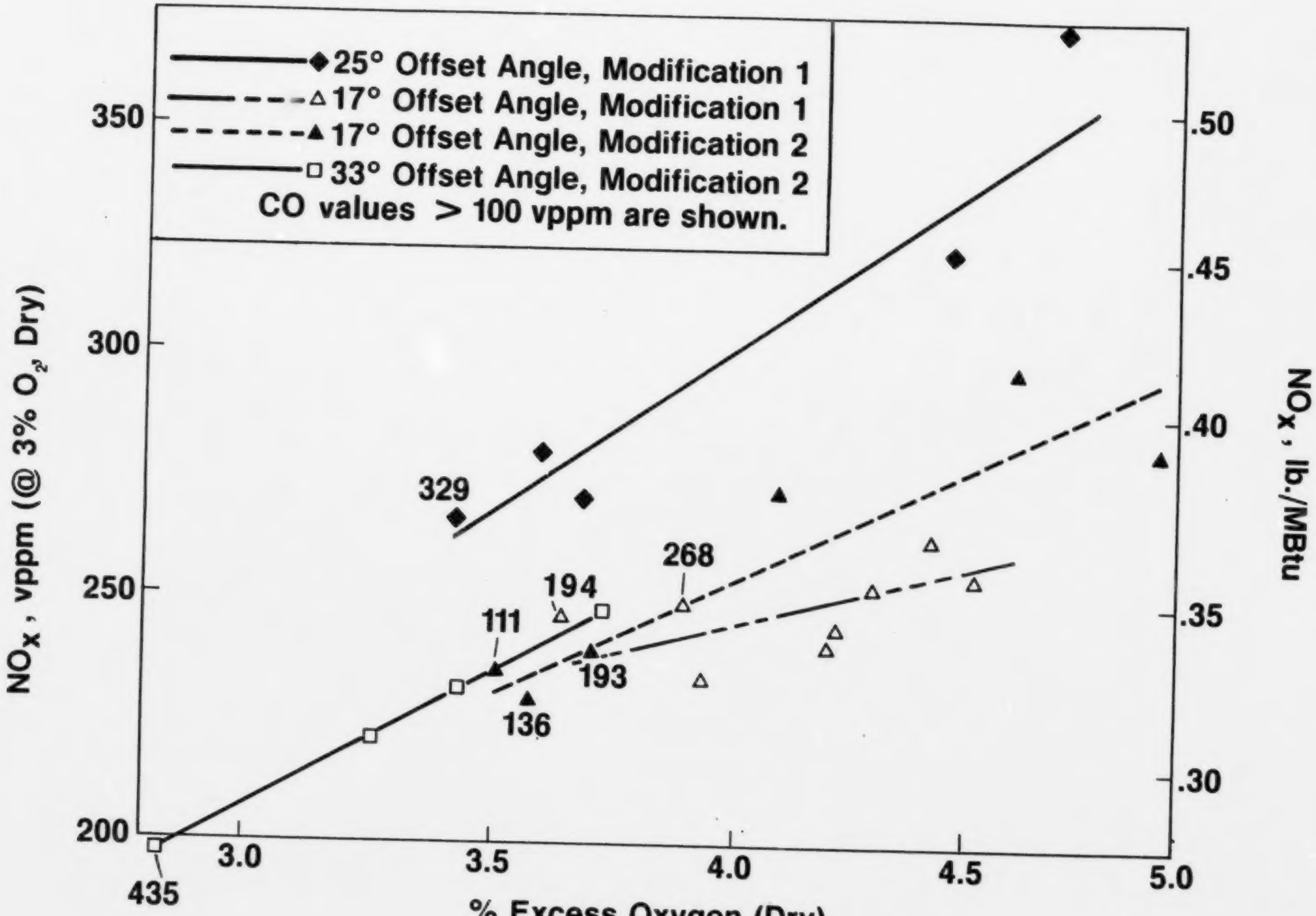

Figure D-13
Effect of LNCFS Offset Angle on NO_x Levels
(Deep Staging Conditions)

1084-3-354

TABLE D-14
DATA FOR FIGURE D-13
EFFECT OF LNCFS OFFSET ANGLE ON NOx LEVELS
(DEEP STAGING CONDITIONS)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM
25 Degree Offset Angle, Modification 1														
216	422	5	100	5.5	100	25	30	-15	40	0	0	3.56	284	15
219	420	5	100	5.6	100	25	30	-15	37	0	0	3.66	274	22
223	420	5	100	5.1	100	25	30	-15	39	0	0	4.46	327	15
224	420	5	100	5.2	100	25	30	-15	45	0	0	4.64	383	28
257	433	5	100	5.4	100	25	30	-13	36	0	0	3.37	269	329
17 Degree Offset Angle, Modification 1														
255	418	5	100	5.5	100	17	30	-15	30	0	0	3.61	247	194
261	420	5	100	5.7	100	17	30	-15	26	50	0	4.19	242	8
262	420	5	100	6.3	100	17	30	-15	26	50	0	4.21	246	28
263	426	5	100	5.8	100	17	30	-15	30	0	0	3.87	251	268
264	419	5	100	6.1	100	17	30	-15	26	0	26	3.92	235	100
265	419	5	100	6.2	100	17	30	-15	20	50	20	4.29	255	26
268	420	5	100	6.1	100	17	30	-23	30	0	30	4.42	266	29
269	420	5	100	5.9	100	17	30	-23	30	0	30	4.51	257	31
17 Degree Offset Angle, Modification 2														
311	411	5	100	5.5	100	17	30	-16	24	50	24	3.68	240	193
312	407	5	100	5.5	100	17	30	-16	20	100	20	3.54	230	136
331	427	5	100	5.5	100	17	30	-15	28	50	28	3.47	236	111
332	427	5	100	5.5	100	17	30	-15	27	50	27	4.60	302	29
333	428	5	100	9.0	100	17	30	-15	17	50	17	4.91	285	25
334	430	5	100	6.0	100	17	30	-15	26	50	26	4.08	276	43
33 Degree Offset Angle, Modification 2														
302	398	5	100	5.5	100	33	30	-15	20	50	20	3.69	250	62
303	399	5	100	5.5	100	33	30	-15	16	50	16	3.20	221	61
304	399	5	100	5.5	100	33	30	-15	16	50	16	3.38	233	90
313	408	5	100	5.5	100	33	30	-16	16	100	16	2.71	197	435

boiler operation indicated that the boiler was usually operating in an area of marginal stability (i.e., continually fluctuating oxygen and temperature imbalances). Such operation would not be acceptable during long-term operation. Therefore, part way through Modification 2 testing, it was decided that the potential NO_x reductions accomplished by using offset angles of $\geq$17° were not worth the accompanying possible high CO levels and boiler instability. Thereafter, testing was conducted utilizing a minimum (8°) offset angle to better focus on other parametric effects.

The results discussed above indicate that the effect of the LNCFS offset angle on NO_x is strongly related to the other boiler operating parameters. While there are distinctive NO_x reductions and trends at certain conditions, the trends were not seen at some similar conditions. Large offset angles (> 17°) appear to further complicate the boiler aerodynamics which were already complicated by the low-NO_x hardware and operational modifications instituted in this program. This increased complexity may be responsible for certain boiler instabilities (e.g., oxygen and temperature imbalances and fluctuations, and high CO levels).

E. Effects of Burner Tilt and Overfire Air Compartment Tilt on NO_x Levels

The effect of burner tilt on NO_x levels for non-overfire air, Modification 1 tests are shown in Figures D-14 and D-15. The data for these figures are listed in Tables D-15 and D-16, respectively. Because excess oxygen levels varied significantly for these tests, NO_x levels have been corrected to a more common excess oxygen operating level (4.0%) in both plots in order to better evaluate the burner tilt trends. In making the correction to 4% O_2, the average linear relationship shown

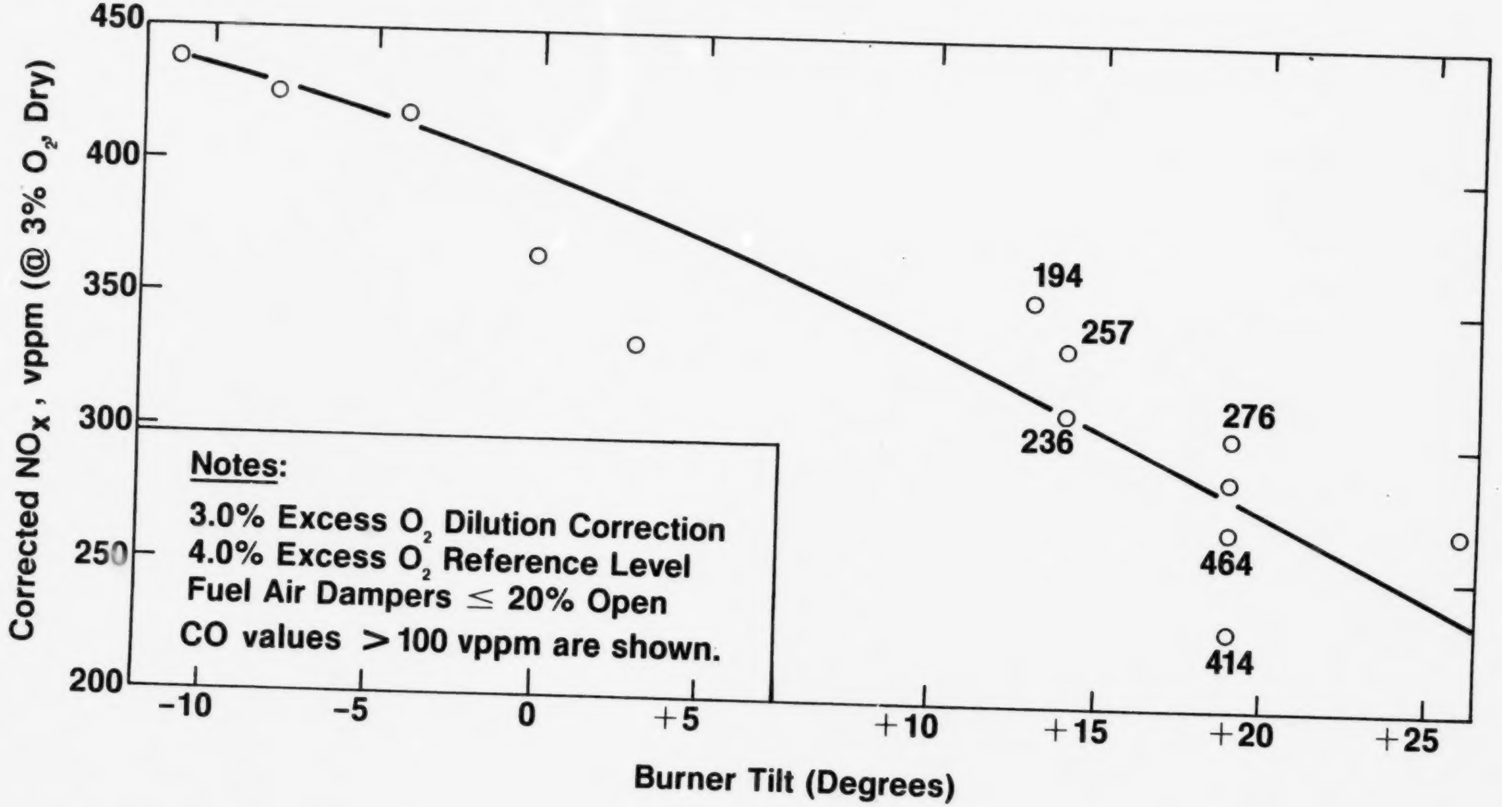

Figure D-14
Effect of Burner Tilt on NO$_X$ Levels
(Non-Overfire Air, Modification 1 Results
with 17° Offset and Fuel Air Dampers Nearly Closed)

TABLE D-15
DATA FOR FIGURE D-14
EFFECT OF BURNER TILT ON NOx LEVELS
(NON-OVERFIRE AIR, MODIFICATION 1 RESULTS WITH ALL FIVE FUEL ELEVATIONS IN USE AND FUEL AIR DAMPERS NEARLY CLOSED)

TEST NO.	MWE GROSS	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	CORRECTED NOx, VPPM	NOTES
140	421	10	5.5	0	17	0	-4	60	25	0	4.02	418	14	417	1
142	424	10	5.5	0	33	0	19	97	100	0	4.56	316	84	285	1
144	423	10	5.6	0	25	0	26	100	100	0	4.83	315	98	269	2
154	425	20	5.5	0	17	0	14	50	100	0	3.49	306	257	334	2
155	424	10	5.5	0	17	0	13	60	100	0	3.42	320	194	352	2
159	426	20	5.5	0	25	0	-11	53	100	0	3.65	420	13	439	2
160	424	10	5.6	0	25	0	-8	60	100	0	3.58	402	22	425	2
162	426	20	5.5	0	33	0	14	94	100	0	4.06	313	236	310	2
167	422	20	5.5	0	33	0	19	80	100	0	4.14	309	276	301	2
168	418	10	6.5	0	33	0	19	100	100	0	4.08	271	464	267	2
180	425	20	5.5	0	17	0	0	55	100	0	4.75	406	15	365	2
181	421	10	5.5	0	17	0	3	62	100	0	4.72	373	11	333	2
187	420	10	5.5	0	25	0	19	64	100	0	4.95	281	414	229	2

Notes:

1. Top FAD open 100%.
2. Due to ignition point encroachment, the FAD at the left rear corner of elevation 1 was opened 100%.

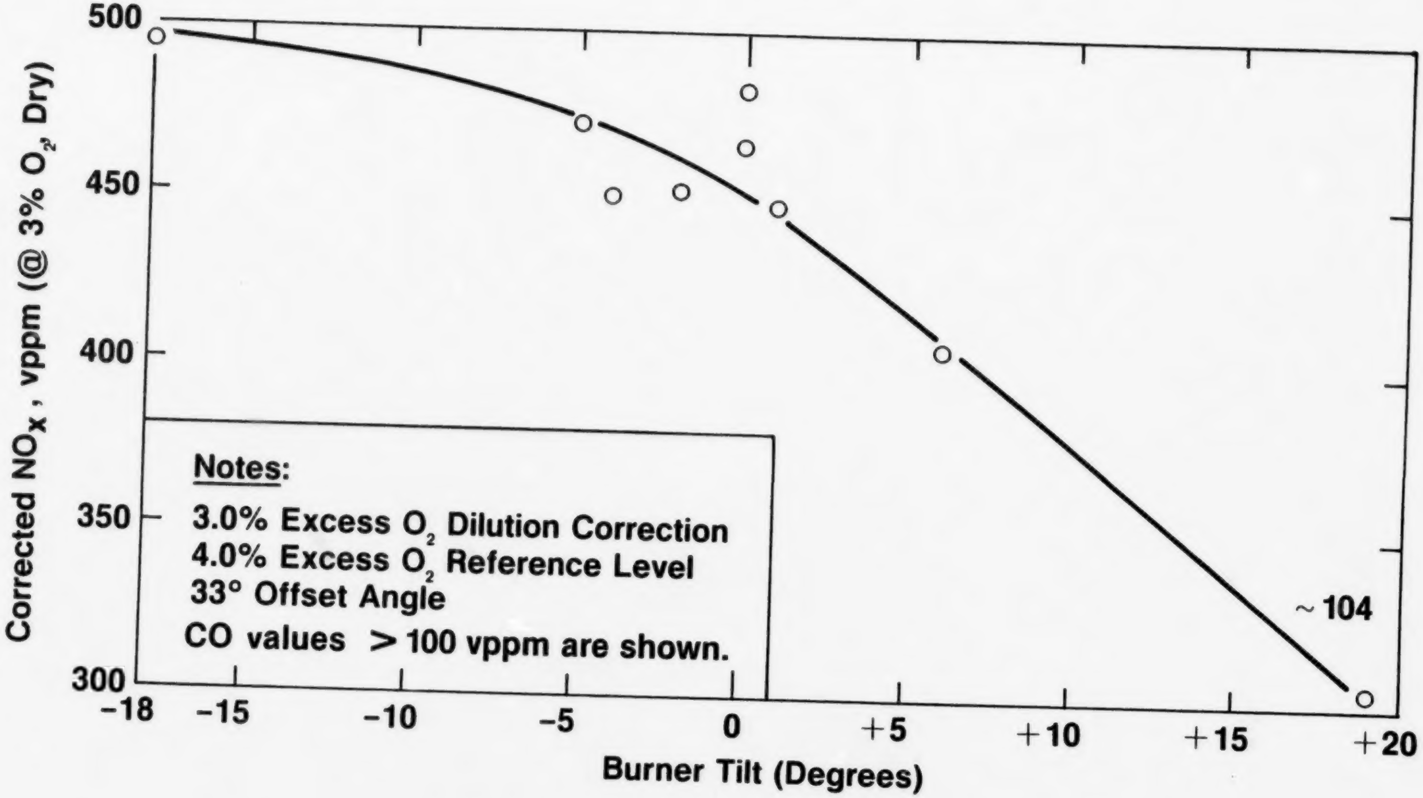

Figure D-15
Effect of Burner Tilt on NO_x Levels
(Non-Overfire Air, Modification 1 Results
with Fuel Air Dampers at 100% and 33° Offset Angle)

TABLE D-16
DATA FOR FIGURE D-15
EFFECT OF BURNER TILT ON NOx LEVELS
(NON-OVERFIRE AIR, MODIFICATION 1 RESULTS WITH 33 DEGREE OFFSET AND ALL FIVE FUEL ELEVATIONS IN USE)

TEST NO.	MWE GROSS	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CORRECTED NOx,VPPM	CO VPPM	NOTE
106	406	100	5.0	0	33	0	1	40	0	40	3.75	434	448	12	
125	405	100	5.5	0	33	0	-5	40	50	40	3.82	462	472	10	
129	420	100	5.5	0	33	0	-2	60	0	0	3.88	445	452	10	
132	429	100	5.5	0	33	0	-4	50	0	0	2.95	392	450	13	
164	427	100	5.5	0	33	0	-18	50	100	0	3.45	465	495	22	
165	419	100	5.5	0	33	0	19	100	100	0	5.54	390	305	104	1
170	426	100	5.5	0	33	0	6	60	100	0	4.46	430	405	14	
242	425	100	5.4	0	33	0	0	48	50	48	4.13	489	482	12	
243	409	100	5.4	0	33	0	0	46	50	46	4.35	485	466	23	

NOTE:

1. CO reading suspect due to a possible rotameter leak.

in Section II-A of a 55 vppm NO_x decrease per 1% decrease in excess oxygen was used. (Note that this is not a dilution correction and it should not be confused with the standard dilution calculation used to factor out excess air in order to put values on a 3% O_2 basis. Both corrections have been applied in this case [Figures D-14 and D-15].)

In Figure D-14, the corrected NO_x levels are plotted against burner tilt for tests run at offset angles of $\geq$17° and fuel air damper settings of $\leq$20% open. The figure shows an apparent trend toward decreasing NO_x with increasing burner tilt. This trend is also shown in Figure D-15 for tests run at a constant 33° offset angle with fuel air damper settings of 100% open.

The effect of burner tilt on NO_x levels for non-overfire air Modification 2 tests is shown in Figure D-16. The data for this figure are listed in Table D-17. As in the Modification 1 case, NO_x levels decreased with increasing burner tilt. In this case, a reduction of 20 vppm per 10° increase in burner tilt is shown.

The NO_x versus burner tilt trend established for non-overfire air operation in both Modifications 1 and 2 is not similar to that demonstrated during baseline testing. The reasoning for this reversal lies in the burner tilt theory. Burner tilts are automatically controlled to maintain constant reheat outlet steam temperatures. The tilts compensate mainly for variations in load and for the effects of slag buildup. In the case of the boiler modifications, however, the burner tilts may also change for other thermal/kinetic reasons as well. This is because of the increased complexity of the boiler aerodynamics caused by the hardware and operation modifications. In any event, as burner tilts are varied, they affect heat transfer rates in different parts of the boiler to different degrees.

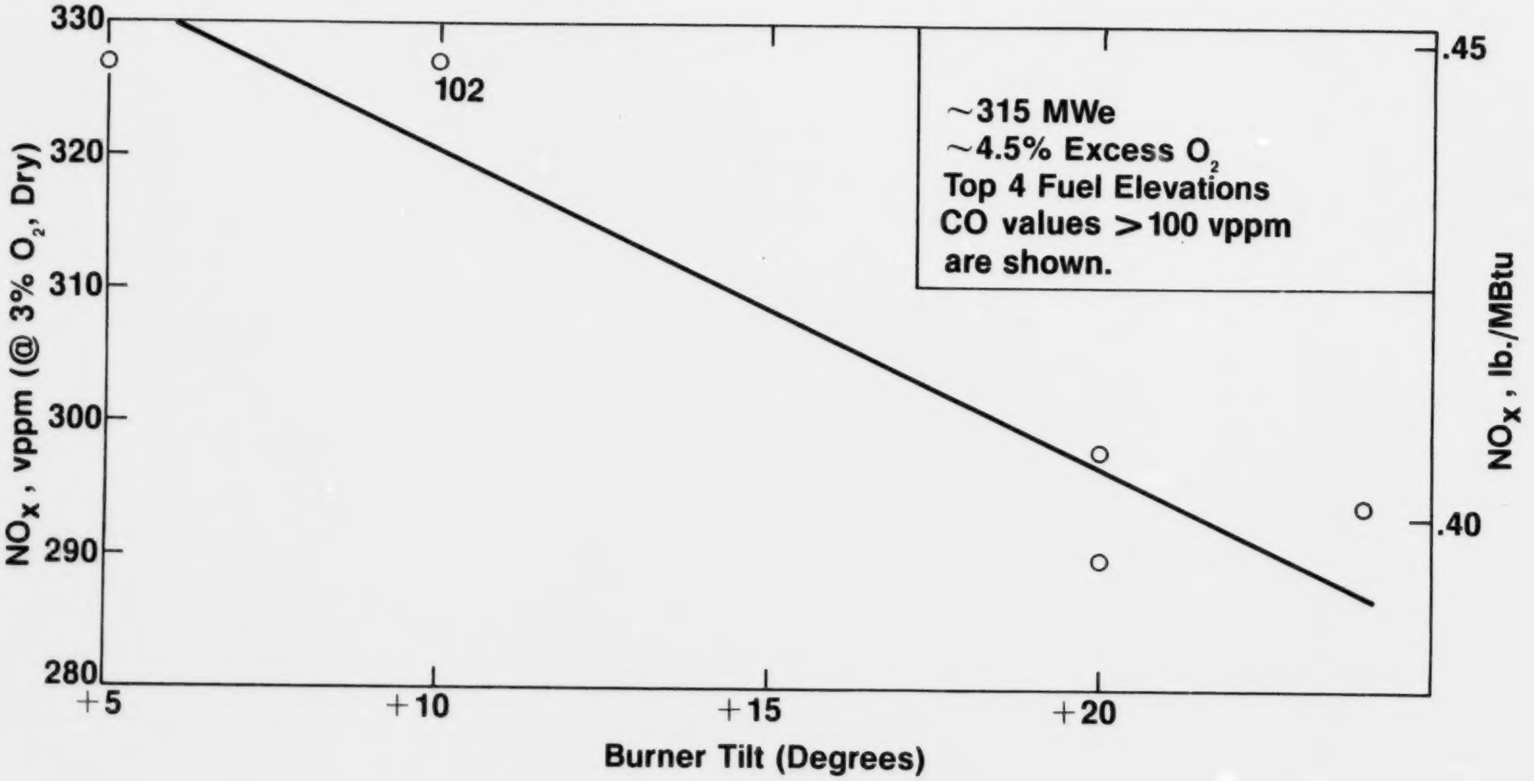

Figure D-16
Effect of Burner Tilt on NO$_X$ Levels
(Non-Overfire Air, Modification 2 Results)

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TABLE D-17
DATA FOR FIGURE D-16
EFFECT OF BURNER TILT ON NOx LEVELS
(NON-OVERFIRE AIR, MODIFICATION 2 RESULTS USING UPPER FOUR FUEL ELEVATIONS ONLY)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT 02	NOX VPPM	CO VPPM	NOTES
362	299	4	80	3.3	0	17	0	24	35	50	35	4.50	294	65	1
379	320	4	90	5.0	0	8	0	10	30	50	30	4.49	327	102	2
380	314	4	90	5.0	0	8	0	20	35	50	35	4.40	290	95	
381	313	4	90	5.0	0	8	0	5	35	50	35	4.64	327	59	
382	315	4	90	3.7	0	8	0	20	33	50	33	4.58	298	70	

Notes:

1. Top auxiliary air compartments (AUX 1) were on automatic, and at an 8 degree offset angle.
2. Oxygen level in probe assembly No. 4 vascillated between 3.5% and 7.0% during the test.

While these effects may not change peak flame temperatures much, they displace the combustion zone temperature profile within the boiler. This may also offset the time/temperature profile of the combustion zone. Since these changes affect both the reaction kinetics of fuel nitrogen conversion and the degree of thermal NO_x formation (although to a small extent), NO_x may or may not show a trend (in either direction) relative to burner tilt.

The fact that post-modification NO_x levels decrease with increasing burner tilts for non-overfire air operation is significant when considering operation at reduced loads. For loads of <250 MW_e (i.e., when overfire air is not used), reheat outlet steam temperatures are maintained by tilting the burners upward, which in turn reduces NO_x levels.

In overfire air operation, the kinetic effects of staging have a significant effect on NO_x levels. In this case, the angle differential between the overfire air compartment tilts and the burner tilts is the controlling factor. The effect of angle differential on NO_x for Modification 1 testing is shown in Figure D-17. The data are listed in Table D-18. This plot shows that an increase of 30° in differential angle (i.e., a change from an average degree of staging to a moderate degree of staging) yielded NO_x decreases of approximately 40 vppm. However, the three moderate staging tests all yielded high CO levels.

Results from other Modification 1 tests generally confirmed this NO_x versus differential angle trend. However, many test results did not always follow such a distinctive pattern throughout the differential angle range. This can be explained by parametric interactions. For example, for a given set of tests run at a constant overfire air compartment tilt, it was

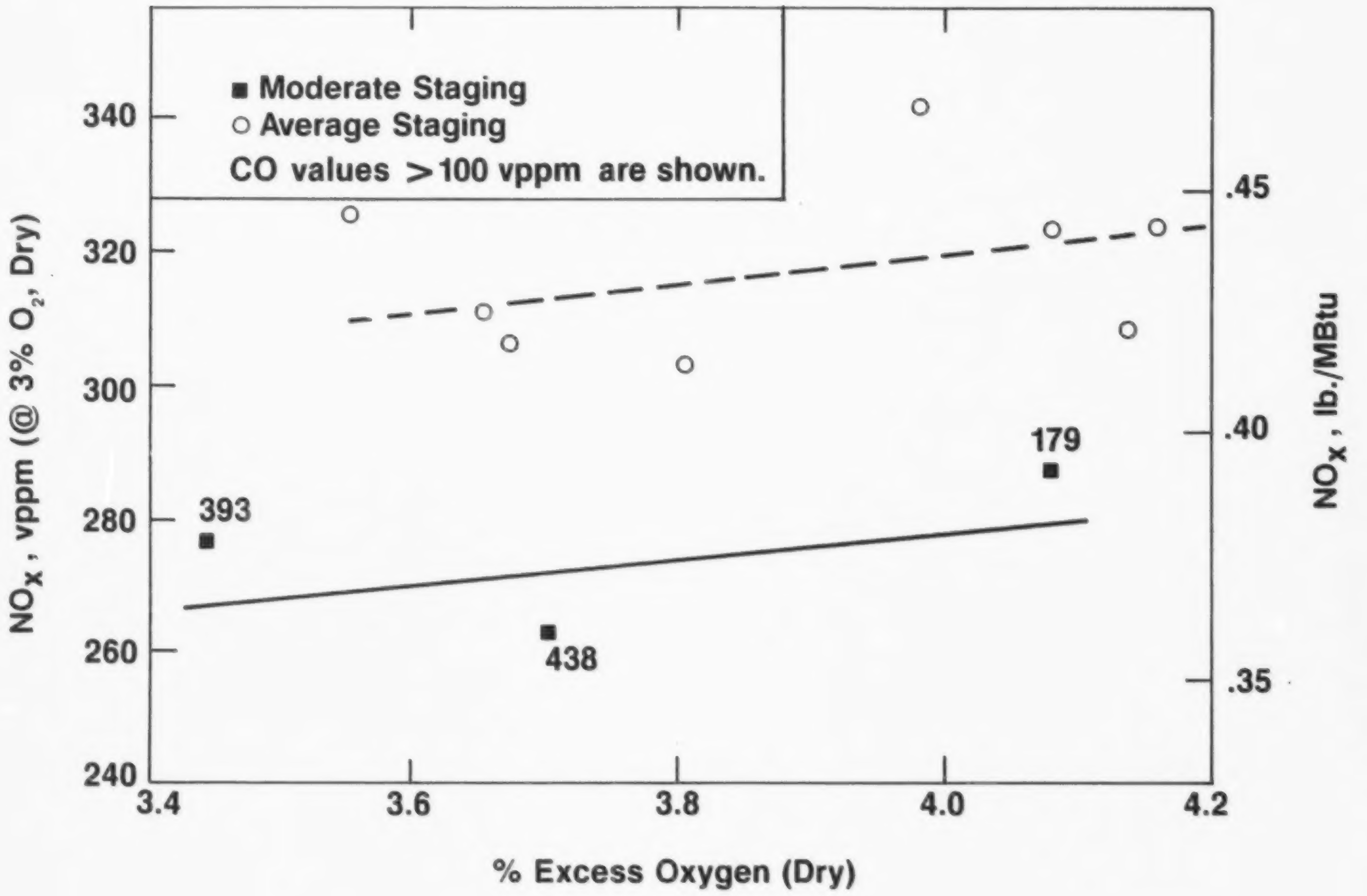

Figure D-17
Effects of Angle Differential on NO_x Levels
(Modification 1 Results)

TABLE D-18
DATA FOR FIGURE D-17
EFFECT OF ANGLE DIFFERENTIAL ON NOx LEVELS
(MODIFICATION 1 RESULTS)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT 02	NOX VPPM	CO VPPM
						Average Staging								
202	428	5	100	5.6	100	25	0	0	45	0	0	3.79	327	32
203	427	5	50	5.3	100	25	0	0	47	0	0	4.08	323	34
204	418	5	20	5.6	100	25	0	0	49	0	0	4.14	309	14
206	419	5	100	3.7	100	25	0	0	70	0	0	4.16	323	18
207	424	5	100	5.2	100	25	0	0	42	0	0	3.80	303	68
208	423	5	100	5.5	50	25	0	0	48	0	0	3.98	341	16
209	425	5	100	5.4	50	25	0	0	44	0	0	3.55	325	66
210	422	5	50	5.5	50	25	0	0	45	0	0	3.65	311	31
						Moderate Staging								
217	420	5	100	5.5	100	25	30	0	37	0	0	3.44	277	393
258	432	5	100	5.5	100	25	30	0	35	0	0	3.70	263	438
259	434	5	100	6.0	100	25	30	0	35	0	0	4.08	287	179

noticed that as the burner tilts are raised, the degree of staging is decreased. This would suggest that NO_x levels would increase. Conversely, for non-overfire air operation, NO_x levels were shown to decrease as the burner tilts were raised. Therefore, the NO_x versus differential angle trend would depend on the relative strengths of these two opposing effects. The fact that many tests did not conform to either trend throughout the differential angle range suggests comparable but varying effects. These effects may also be tied into other operating parameters.

The effect of differential angle on NO_x levels for Modification 2 overfire air testing is shown in Figure D-18 at three different load and excess oxygen conditions. The data are listed in Table D-19. Plotted as NO_x levels versus differential angle, the figure clearly shows a definite decrease in NO_x levels with increasing differential angle. This was also seen for Modification 1. The decrease in NO_x is about 25 vppm per 10° increase. Also note that all of these tests yielded acceptable CO levels.

In reviewing the NO_x versus differential angle trend, in the case of baseline and Modification 1 testing, distinct trends were not seen throughout the range of differential angles. Instead, a significant increase in differential angle was required ($\geq$30°) to achieve modest NO_x reductions ($\leq$40 vppm). On the other hand, Modification 2 testing demonstrated a distinct NO_x versus differential angle trend throughout the differential angle range. These Modification 2 tests also demonstrated a NO_x reduction capability of about 2 times that of the baseline and Modification 1 testing (i.e., a reduction of $\geq$80 vppm per 30° increase in differential angle).

Because the degree of staging and potential NO_x reductions

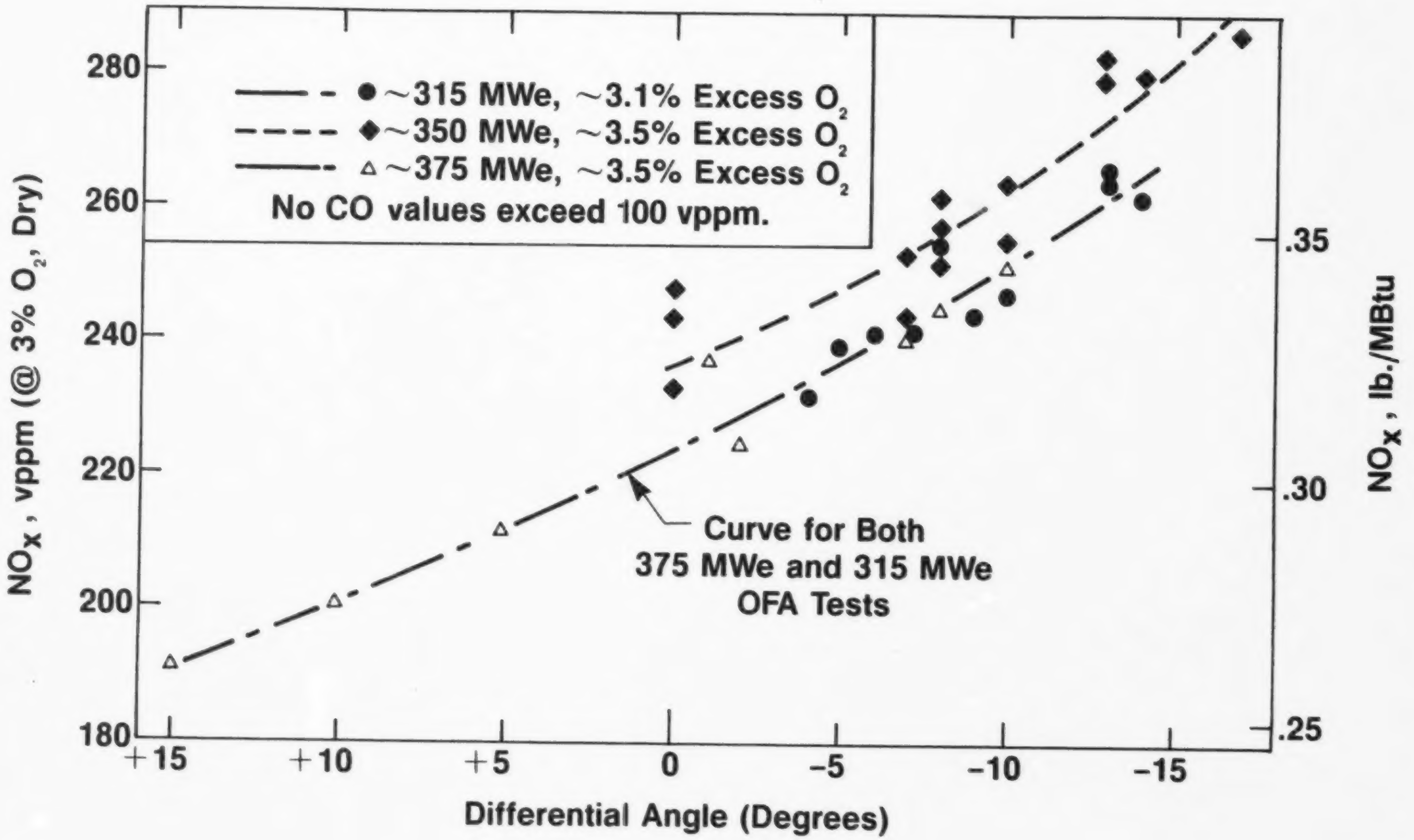

Figure D-18
Effect of Differential Angle on NO_x Levels
(Modification 2 Results)

TABLE D-19
DATA FOR FIGURE D-18
EFFECT OF DIFFERENTIAL ANGLE ON NOx LEVELS
(MODIFICATION 2 RESULTS)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
							~315 MWe								
504	320	5	100	3.1	100	8	10	20	0	50	0	3.05	247	19	1
505	320	5	100	3.4	100	8	10	17	0	50	0	3.02	241	21	1
506	320	5	100	3.3	100	8	10	16	0	50	0	3.07	241	24	1
507	321	5	100	3.2	100	8	10	15	0	50	0	3.05	239	27	1
508	320	5	100	3.0	100	8	10	18	0	50	0	3.12	254	21	1
509	310	5	100	2.5	100	8	10	19	0	50	0	3.09	244	22	1
513	327	5	100	4.0	100	8	10	14	0	0	0	3.28	232	44	1
537	314	5	100	3.4	50	8	10	24	0	40	0	3.11	251	31	1
538	314	5	100	2.8	100	8	10	23	0	40	0	3.39	265	22	1
542	325	5	100	4.5	50	8	10	23	1	40	1	3.23	264	50	1
							~350 MWe								
376	355	5	90	5.5	100	8	10	10	0	50	0	3.68	244	72	
377	349	5	90	5.0	100	8	10	10	0	50	0	3.68	233	71	
394	351	5	90	5.4	100	8	10	24	0	50	0	3.84	279	46	
395	350	5	90	5.4	100	8	10	23	0	50	0	3.72	280	55	
396	352	5	90	5.2	100	8	10	20	0	50	0	3.45	264	53	
397	350	5	90	5.2	100	8	10	20	0	50	0	3.31	253	56	
398	350	5	90	5.2	100	8	10	18	0	50	0	3.24	252	53	
399	352	5	90	5.6	100	8	10	10	0	50	0	3.68	247	56	
400	354	5	90	4.8	100	8	10	27	0	50	0	3.88	286	68	
401	350	5	90	4.8	100	8	10	23	0	50	0	3.78	282	58	
402	354	5	90	4.8	100	8	10	18	0	50	0	3.38	257	60	
403	350	5	90	4.8	100	8	10	18	0	50	0	3.42	261	60	
404	353	5	90	4.6	100	8	10	17	0	50	0	3.32	252	60	
405	356	5	90	4.6	100	8	10	17	0	50	0	3.01	243	57	
							~375 MWe								
386	375	5	90	5.5	100	8	10	18	5	50	5	3.61	245	65	
387	375	5	90	5.5	100	8	10	12	5	50	5	3.52	224	55	
388	375	5	90	5.5	100	8	10	20	0	50	0	3.72	251	60	
389	375	5	90	5.5	100	8	10	11	10	50	10	3.60	236	62	
390	375	5	90	5.6	100	8	10	5	10	50	10	3.46	211	56	
391	375	5	90	5.6	100	8	10	0	8	50	8	3.40	200	57	
392	375	5	90	5.6	100	8	10	-5	5	50	5	3.49	192	60	
393	371	5	100	5.5	100	8	10	17	6	50	6	3.64	241	54	

NOTE:

1. Left front burners on elevations 4 and 5, and the right rear burner on elevation 5 were at horizontal orientations (0 degrees) due to broken linkages.

decrease with decreasing differential angle, and because both Modification 1 and 2 non-overfire air tests yielded decreasing NO_x with increasing burner tilts, one may conclude that at high burner tilts, the overfire air and non-overfire air curves will converge. This is demonstrated in Figure D-19 for Modification 2 tests. The data are listed in Table D-20. The significance of this relationship is that at high burner tilts for both Modifications 1 and 2, the effect of overfire air on NO_x reductions is minimal.

F. Effect of Modification 3 on NO_x Levels and Boiler Operating Flexibility

Because Modification 3 was designed to restore some boiler operating flexibility at low-NO_x operating conditions, the discussion on Modification 3 was placed here (following the discussions on boiler operability and burner tilt/overfire air tilt effects). The reasons for this which will become apparent shortly. The effect of Modification 3 on NO_x levels compared to baseline and Modification 2 results is shown in Figure D-20 for non-overfire air tests conducted at about 75% load (261 MW_e to 335 MW_e). The data are listed in Table D-21. On the average, Modification 3 yielded NO_x reductions of about 70 vppm (at 4.0% excess oxygen) compared with baseline testing. These reductions, however, were not quite as great as the 110 vppm reductions achieved by Modification 2. Note that differences due to burner tilt have not been included here.

The effect of moderate and deep staging on NO_x levels was tested for Modification 3 because these conditions often caused unstable boiler operations for Modification 2. The results are listed in Table D-22, and shown in Figure D-21.

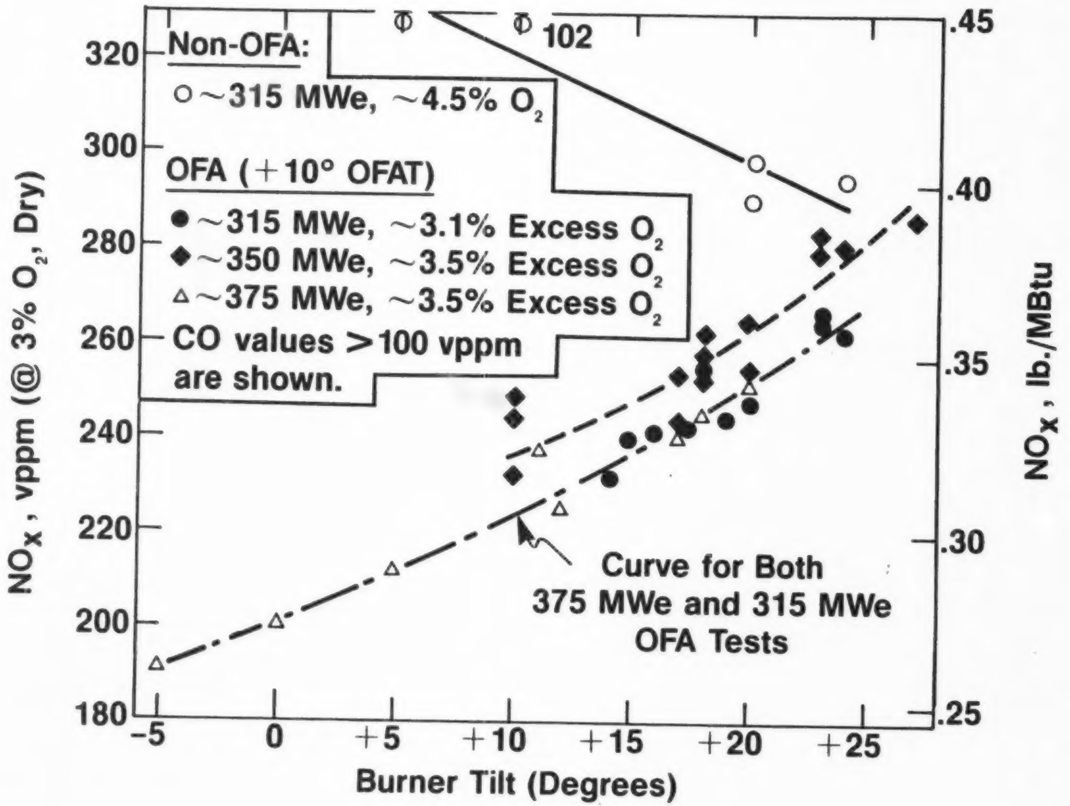

Figure D-19
Comparison of Overfire Air Plus Burner Tilt Effects on NO_x Levels
(Modification 2 Results)

TABLE D-20 (PG 1 OF 2)
DATA FOR FIGURE D-19
COMPARISON OF OVERFIRE AIR AND BURNER TILT EFFECTS ON NOx LEVELS
(MODIFICATION 2 RESULTS)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
							~315 MWe								
362	299	4	80	3.3	0	17	0	24	35	50	35	4.50	294	65	1,2
379	320	4	90	5.0	0	8	0	10	30	50	30	4.49	327	102	2,3
380	314	4	90	5.0	0	8	0	20	35	50	35	4.40	290	95	2
381	313	4	90	5.0	0	8	0	5	35	50	35	4.64	327	59	2
382	315	4	90	3.7	0	8	0	20	33	50	33	4.58	298	70	2
504	320	5	100	3.1	100	8	10	20	0	50	0	3.05	247	19	4
505	320	5	100	3.4	100	8	10	17	0	50	0	3.02	241	21	4
506	320	5	100	3.3	100	8	10	16	0	50	0	3.07	241	24	4
507	321	5	100	3.2	100	8	10	15	0	50	0	3.05	239	27	4
508	320	5	100	3.0	100	8	10	18	0	50	0	3.12	254	21	4
509	310	5	100	2.5	100	8	10	19	0	50	0	3.09	244	22	4
513	327	5	100	4.0	100	8	10	14	0	0	0	3.28	232	44	4
537	314	5	100	3.4	50	8	10	24	0	40	0	3.11	251	31	4
538	314	5	100	2.8	100	8	10	23	0	40	0	3.39	265	22	4
542	325	5	100	4.5	50	8	10	23	1	40	1	3.23	264	50	4
							~350 MWe								
376	355	5	90	5.5	100	8	10	10	0	50	0	3.68	244	72	
377	349	5	90	5.0	100	8	10	10	0	50	0	3.68	233	71	
394	351	5	90	5.4	100	8	10	24	0	50	0	3.84	279	46	
395	350	5	90	5.4	100	8	10	23	0	50	0	3.72	280	55	
396	352	5	90	5.2	100	8	10	20	0	50	0	3.45	264	53	
397	350	5	90	5.2	100	8	10	20	0	50	0	3.31	253	56	
398	350	5	90	5.2	100	8	10	18	0	50	0	3.24	252	53	
399	352	5	90	5.6	100	8	10	10	0	50	0	3.68	247	56	
400	354	5	90	4.8	100	8	10	27	0	50	0	3.88	286	68	
401	350	5	90	4.8	100	8	10	23	0	50	0	3.78	282	58	
402	354	5	90	4.8	100	8	10	18	0	50	0	3.38	257	60	
403	350	5	90	4.8	100	8	10	18	0	50	0	3.42	261	60	
404	353	5	90	4.6	100	8	10	17	0	50	0	3.32	252	60	
405	356	5	90	4.6	100	8	10	17	0	50	0	3.01	243	57	

TABLE D-20 (PG 2 OF 2)
DATA FOR FIGURE D-19
COMPARISON OF OVERFIRE AIR AND BURNER TILT EFFECTS ON NOx LEVELS
(MODIFICATION 2 RESULTS)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
						~375 MWe									
386	375	5	90	5.5	100	8	10	18	5	50	5	3.61	245	65	
387	375	5	90	5.5	100	8	10	12	5	50	5	3.52	224	55	
388	375	5	90	5.5	100	8	10	20	0	50	0	3.72	251	60	
389	375	5	90	5.5	100	8	10	11	10	50	10	3.60	236	62	
390	375	5	90	5.6	100	8	10	5	10	50	10	3.46	211	56	
391	375	5	90	5.6	100	8	10	0	8	50	8	3.40	200	57	
392	375	5	90	5.6	100	8	10	-5	5	50	5	3.49	192	60	
393	371	5	100	5.5	100	8	10	17	6	50	6	3.64	241	54	

Notes:

1. Top auxiliary air compartments (AUX 1) were on automatic, and at an 8 degree offset angle.
2. Upper four fuel elevations used.
3. Oxygen level in probe assembly No. 4 vascillated between 3.5% and 7.0% during the test.
4. Left front burners on elevations 4 and 5, and the right rear burner on elevation 5 were at horizontal orientations (0 degrees) due to broken linkages.

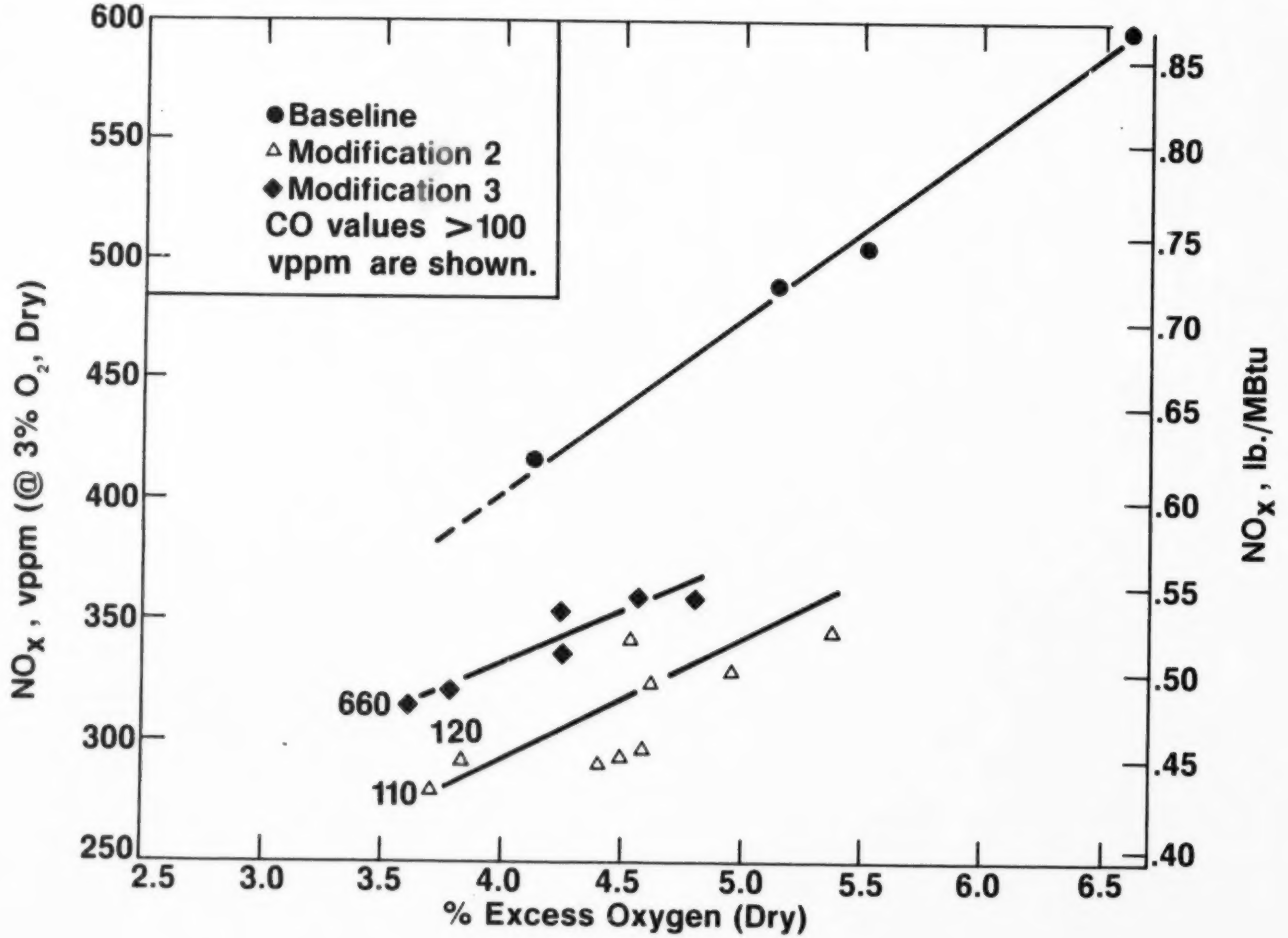

Figure D-20
Effect of Modification 3 on NO$_x$ Levels
(Non-Overfire Air Operation at About 75% Load)

TABLE D-21
DATA FOR FIGURE D-20
EFFECT OF MODIFICATION 3 ON NOx LEVELS
(NON-OVERFIRE AIR OPERATION AT ABOUT 75% LOAD)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
Baseline															
59	300	4	85	2.7	0	0	0	0	0	60	0	5.13	489	15	1
60	302	4	100	4.0	0	0	0	0	0	60	0	5.51	506	14	1
61	301	4	100	3.2	0	0	0	0	0	60	0	4.13	416	20	1
62	299	4	100	4.8	0	0	0	0	8	60	8	6.62	596	13	1
Modification 2															
362	299	4	80	3.3	0	17	0	24	35	50	35	4.50	294	65	1,2
363	296	4	70	3.7	0	17	0	24	31	50	31	3.71	281	110	1,2
378	335	5	90	5.0	0	8	0	10	30	50	30	3.88	288	120	
380	314	4	90	5.0	0	8	0	20	35	50	35	4.40	290	95	1
381	313	4	90	5.0	0	8	0	5	35	50	35	4.64	327	59	1
382	315	4	90	3.7	0	8	0	20	33	50	33	4.58	298	70	1
515	326	5	100	4.4	0	8	0	12	18	40	18	5.23	357	31	3
516	327	5	100	6.5	0	8	0	10	6	40	6	5.09	379	31	3
528	320	4	100	4.5	0	8	0	15	24	40	24	5.38	345	48	1,3
529	323	4	100	4.5	0	8	0	20	20	40	20	4.96	329	33	1,3
534	273	4	100	3.5	0	8	0	24	12	40	12	4.53	344	31	1,3
Modification 3															
604	310	4	100	3.9	0	8	0	21	24	25	24	3.61	315	660	1,4
605	319	4	100	4.2	0	8	0	0	26	25	26	3.79	319	23	1
617	310	4	100	4.4	0	8	0	0	22	25	22	4.25	338	20	5
618	270	4	100	2.9	0	8	0	0	23	25	23	4.80	358	17	1
619	270	4	100	3.0	0	8	0	16	16	25	16	4.22	354	27	1
620	261	4	100	2.6	0	8	0	25	19	25	19	4.59	361	25	1

Notes:

1. Upper four fuel elevations used.
2. Top auxiliary air compartments were on automatic, and at an 8 degree offset angle.
3. Left front burners on elevations 4 and 5, and the right rear burner on elevation 5 were at horizontal orientations (0 degrees) due to broken linkages.
4. Large oxygen imbalance.
5. Mill No. 4 out of service.

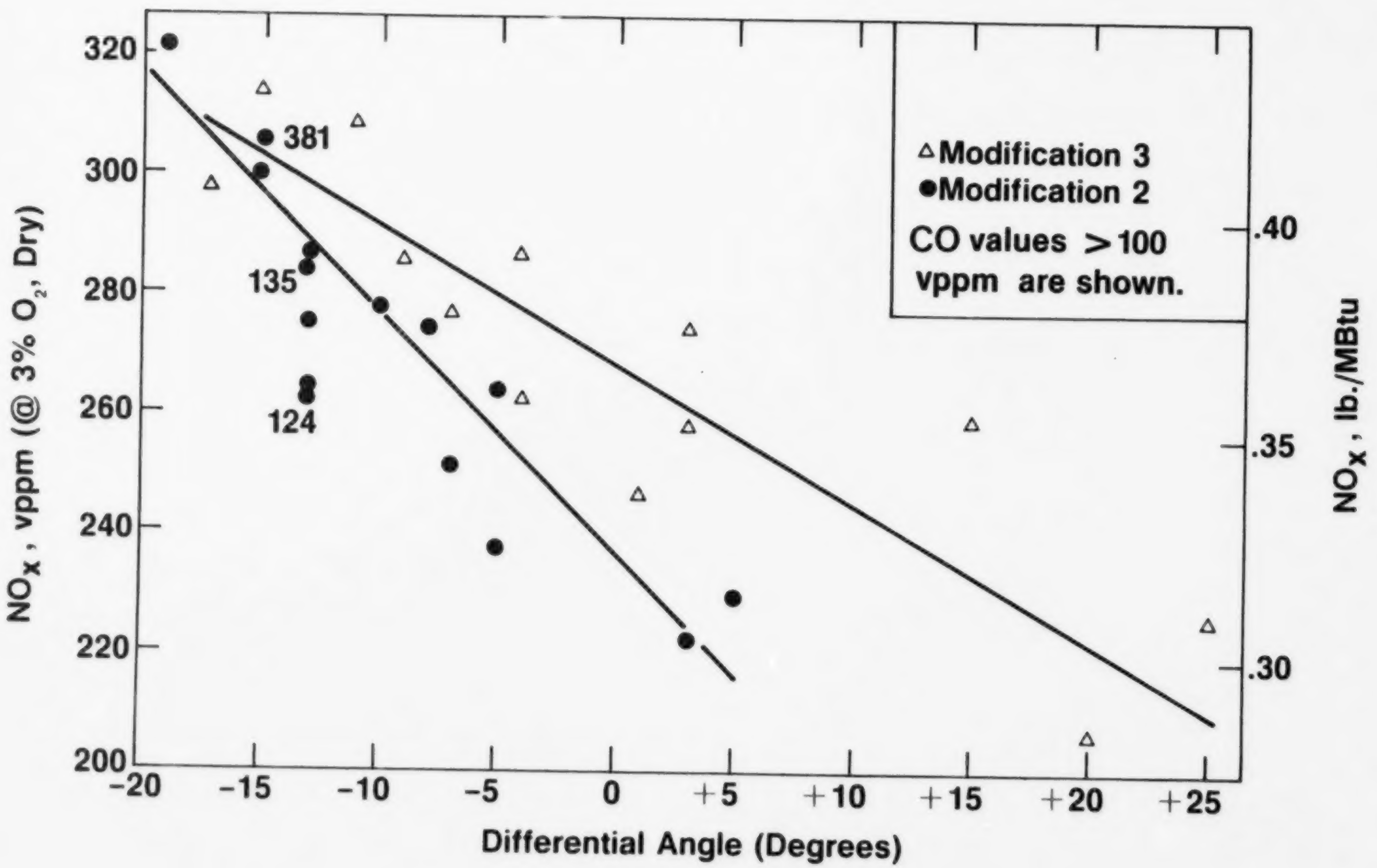

Figure D-21
Effect of Modification 3 on NO_x Levels
for Overfire Air Operation at About 75% Load
(NO_x vs Differential Angle...Comparison of Mod. 3 and Mod. 2 Results)

1084-3-335

TABLE D-22
DATA FOR FIGURE D-21
EFFECT OF MODIFICATION 3 ON NOx LEVELS FOR OVERFIRE AIR OPERATION AT ABOUT 75% LOAD USING UPPER FOUR FUEL ELEVATIONS ONLY
(NOx VS DIFFERENTIAL ANGLE, COMPARISON OF MOD 3 AND MOD 2 RESULTS)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
Modification 2															
383	322	4	90	- 5.2	100	8	10	5	12	50	12	4.31	229	68	
384	335	4	90	4.5	100	8	0	7	10	50	10	4.01	251	50	
385	330	4	90	3.5	100	8	10	7	0	50	0	3.85	222	51	
502	285	4	100	---	100	8	10	15	-	50	-	3.91	264	22	1
503	285	4	100	---.	100	8	10	15	-	50	-	3.02	237	33	1
522	320	4	100	4.5	70	8	0	15	5	40	5	4.15	300	26	1
523	320	4	100	4.5	70	8	0	19	5	40	5	4.26	321	58	1
524	320	4	100	4.5	70	8	0	10	2	40	2	3.76	278	28	1
525	320	4	100	4.5	70	8	10	23	2	40	2	4.12	284	135	1
526	320	4	100	4.5	70	8	10	18	2	40	2	3.61	275	32	1
535	321	4	100	4.0	100	8	10	25	0	40	0	3.76	305	36	1,2
536	317	4	100	4.6	50	8	10	23	0	40	0	3.55	287	27	1,2
543	320	4	100	4.4	50	8	10	23	5	40	5	3.87	275	37	1
544	321	4	100	4.3	50	8	10	23	3	40	3	3.45	264	65	1
545	320	4	100	4.3	50	8	10	23	2	40	2	3.67	263	124	1
Modification 3															
601	324	4	100	3.8	100	8	3	7	0	25	0	3.32	263	24	
602	325	4	100	3.9	100	8	3	12	0	25	0	3.78	259	19	
603	308	4	100	2.8	100	8	3	0	0	25	0	3.40	258	39	
606	318	4	100	3.5	100	8	3	0	0	25	0	4.06	275	25	
607	321	4	100	4.2	100	8	10	9	0	25	0	3.77	247	33	
608	323	4	100	3.7	100	8	10	-10	0	25	0	3.13	206	45	
609	320	4	100	4.1	100	8	10	-15	0	25	0	3.94	226	24	
610	290	4	100	2.8	100	8	5	12	0	25	0	3.51	277	28	
611	316	4	100	3.5	100	8	5	9	2	25	2	4.19	287	26	
612	312	4	100	4.0	35	8	5	20	16	25	16	4.26	314	381	
613	323	4	100	4.2	60	8	5	16	0	25	0	3.59	308	27	
614	297	4	100	3.6	60	8	5	14	0	25	0	3.42	286	19	

Notes:

1. Left front burners on elevations 4 and 5, and the right rear burner on elevation 5 were at horizontal orientation (0 degrees) due to broken linkages.
2. Primary air was flowing through the elevation 5 burners in anticipation of a load (and mill) increase.

The figure shows that Modification 2 yielded lower NO_x levels than Modification 3 at comparable differential angles. However, this data becomes more relevant when considering that all of the Modification 2 and 3 tests were conducted with the boiler's automatic oxygen controller set to ensure that the minimum oxygen concentration in either outlet duct was 3%. Under this condition, Modification 3 tests were able to operate satisfactorily up to differential angles of >20°, and yield NO_x levels of approximately 210 vppm. However, Modification 2 tests could be operated at differential angle levels (overfire air tilt minus burner tilt) up to only +5°, and therefore could reach NO_x levels of only about 220 vppm. More significant, though, is the fact that these Modification 3 tests effected smooth boiler operation, and did not yield any high CO levels. This is in contrast to the Modification 2 tests which caused marginal boiler stability. Also, two of the minimal staging tests performed under Modification 2 resulted in high CO levels.

Modification 3 test results indicate that the hardware changes did restore some of the boiler operating flexibility and stability which was lost with Modification 2. For comparable operating conditions, Modification 3 tests yielded greater NO_x levels than Modification 2 tests. However, the increased boiler operating flexibility of Modification 3 allows the boiler to be run at more extreme low-NO_x (e.g., lower excess air) conditions than were comfortably possible under Modification 2. Thus over the entire recommended operating range of each modification, the increased operating range of Modification 3 somewhat compensates for the Modification 2 effects shown in Figure D-20 and, by decreasing excess air, both modifications were able to achieve comparable NO_x levels before CO emissions increased to unacceptable levels.

G. Effects of Load and Fuel Elevations in Service on NO_x Levels

In evaluating the effect of load on NO_x levels, consideration must be given to the fact that certain operating conditions change with load. The four main parameters which change with load are excess oxygen, overfire air flow, fuel elevations in service, and burner tilts. From full load (~425 MW_e) down to approximately 300 MW_e (280-330 MW_e), these four parameters are not load dependent, and therefore, direct evaluation of load effects can be made. However, below about 300 MW_e, these four parameters are load-restricted, and therefore, load effects on NO_x are best evaluated through restrictions in these parameters.

Results from Modifications 1 and 2 tests run at similar conditions from about 280 MW_e to 430 MW_e indicate negligible effect of load on NO_x levels, except for a narrow load band from about 370 to 390 MW_e (designated hereafter as "~375 MW_e"). In this band, there is a slight, though definite decrease in NO_x levels. This decrease is shown in Figures D-22 and D-18. The data for these figures are listed in Tables D-23 and D-19, respectively. Figure D-22, shows that at deep staging conditions, on the average, tests run at ~375 MW_e yielded NO_x levels that were about 25 vppm lower than in full load tests(>400 MW_e). In Figure D-18, where NO_x levels are plotted against differential angles, the tests run at ~375 MW_e yielded lower NO_x levels (by about 10 vppm) than tests run at ~350 MW_e at the same excess oxygen levels (~3.5%). However, these NO_x levels (at ~375 MW_e from figure D-18) are comparable to tests run at ~315 MW_e, but at a lower excess oxygen (about 3.1%).

The changes in excess oxygen, overfire air and fuel elevations in service with decreasing loads below about 280 MW_e are shown in Figure D-23. The figure shows the original operating pro-

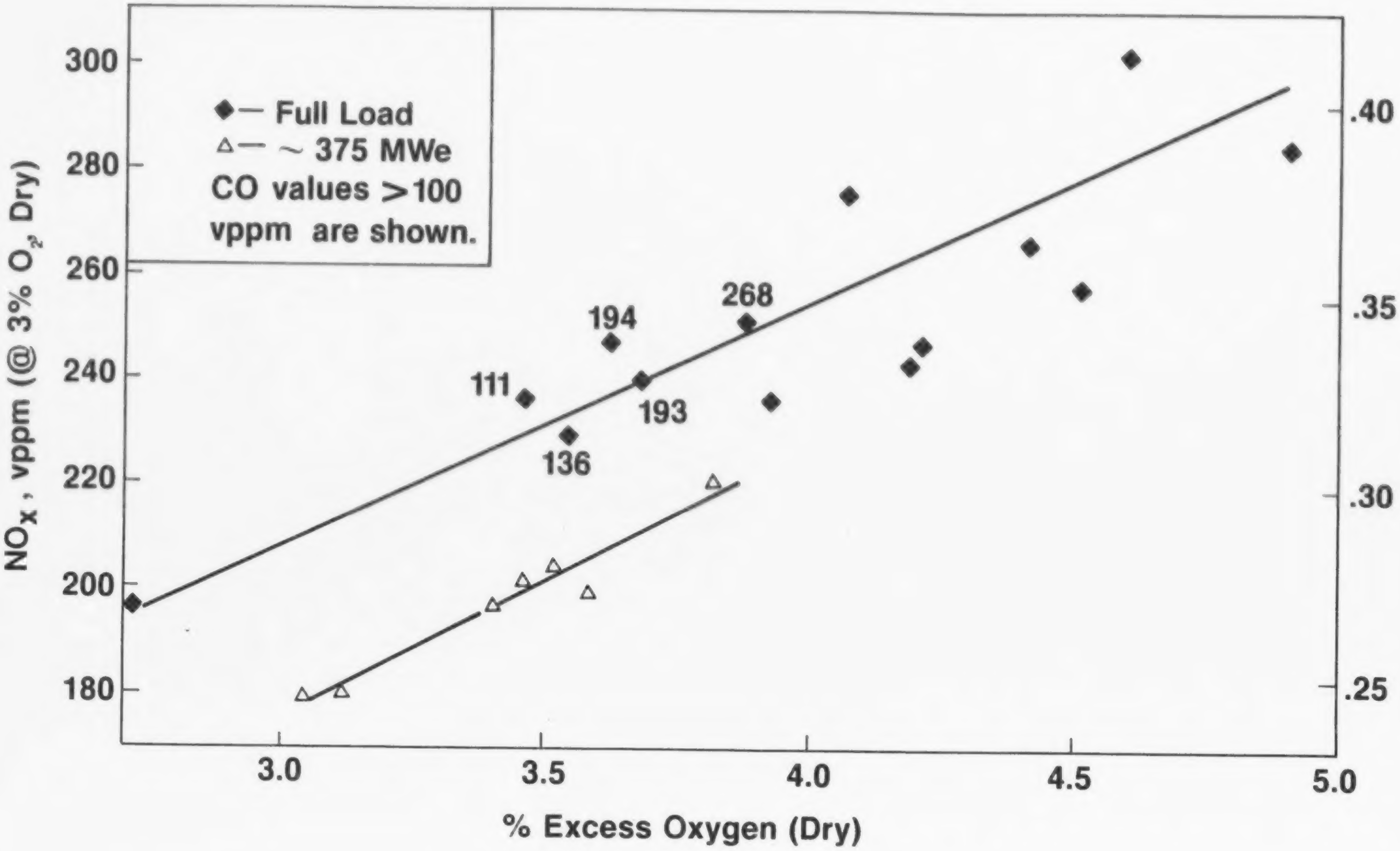

Figure D-22
Effect of Load on NO_x Levels
(Deep Staging Conditions,
Modifications 1 and 2 Results Combined)

TABLE D-23
DATA FOR FIGURE D-22
EFFECT OF LOAD ON NOx LEVELS
(DEEP STAGING CONDITIONS, MODIFICATIONS 1 AND 2 RESULTS COMBINED)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
							Full Load								
255	418	5	100	5.5	100	17	30	-15	30	0	0	3.61	247	194	
261	420	5	100	5.7	100	17	30	-15	26	50	0	4.19	242	8	
262	420	5	100	6.3	100	17	30	-15	26	50	0	4.21	246	28	
263	426	5	100	5.8	100	17	30	-15	30	0	0	3.87	251	268	
264	419	5	100	6.1	100	17	30	-15	26	0	26	3.92	235	100	
265	419	5	100	6.2	100	17	30	-15	20	50	20	4.29	255	26	
268	420	5	100	6.1	100	17	30	-23	30	0	30	4.42	266	29	
269	420	5	100	5.9	100	17	30	-23	30	0	30	4.51	257	31	
311	411	5	100	5.5	100	17	30	-16	24	50	24	3.68	240	193	
312	407	5	100	5.5	100	17	30	-16	20	100	20	3.54	230	136	
331	427	5	100	5.5	100	17	30	-15	28	50	28	3.47	236	111	
332	427	5	100	5.5	100	17	30	-15	27	50	27	4.60	302	29	
333	428	5	100	9.0	100	17	30	-15	17	50	17	4.91	285	25	
334	430	5	100	6.0	100	17	30	-15	26	50	26	4.08	276	43	
							Slightly Less Than Full Load								
266	385	5	100	5.5	100	17	30	-15	12	50	12	3.81	220	39	
322	377	5	100	5.5	100	17	30	-15	8	50	8	3.58	199	64	
323	370	5	100	5.5	100	17	30	-15	0	50	0	3.40	197	82	1
326	379	5	100	5.5	100	25	30	-15	4	50	4	3.52	205	45	
328	374	5	100	5.5	100	25	30	-15	0	50	0	3.04	179	84	
330	369	5	100	5.5	100	17	30	-17	0	50	0	3.46	202	38	

NOTE:

1. Oxygen levels were just at the point where instantaneous CO spikes were occurring.

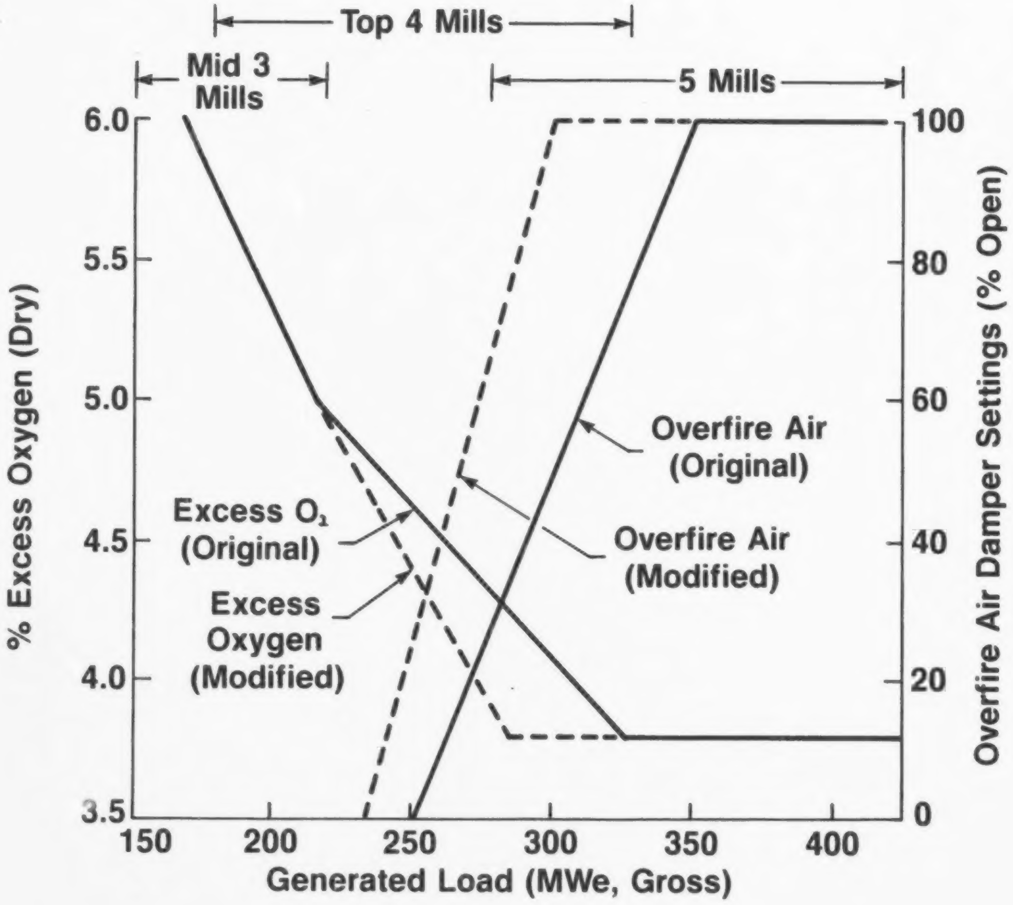

Figure D-23
Excess Oxygen and Overfire Air Operating Profiles

1084-3-342

file submitted to Utah Power and Light Co. by C-E to be carried out during the four 30-day continuous emission monitoring (CEM) tests. It also shows a later modified profile for greater NO_x reductions. In addition to these parameters, consideration must be given to the facts that burner tilts automatically rise at lower loads to maintain reheat outlet steam temperatures, and that at higher burner tilts, non-overfire air and overfire air tests yield comparable NO_x levels (see Figure D-19). Based on these conditions plus the parametric effects on NO_x levels shown previously, predictions would suggest that NO_x levels should continually rise with decreasing loads. However, this increase is not nearly as great as expected. This will be shown in Section III.

A parameter which is directly related to load is fuel elevations in service. Generally, as shown in Figure D-23, the Hunter No. 2 unit operates using the middle 3 fuel elevations for loads up to 200 MW_e (±20 MW_e). Similarly, the top 4 fuel elevations are used for higher loads up to 310 MW_e (± 25 MW_e), and all five fuel elevations are used to carry loads above 310 MW_e. In the ranges from ~285 to 335 MW_e and from ~180 to 220 MW_e, however, there is some flexibility in the choice of fuel elevations.

The effect of fuel elevations in service on NO_x levels in the 285 to 335 MW_e load range is shown in Figure D-24 for Modification 2, overfire air tests. The data are listed in Table D-24. Three cases are shown for minimal staging conditions (i.e., $\leq$ -10° differential angles): 5 fuel elevations, top 4 fuel elevations, and bottom 4 fuel elevations in service. On the average, 5 fuel elevation and top 4 fuel elevation operations yielded similar results, whereas, bottom 4 fuel elvation operation yielded NO_x levels that were about 35 vppm lower. However, bottom 4 fuel elevation operation is not normally

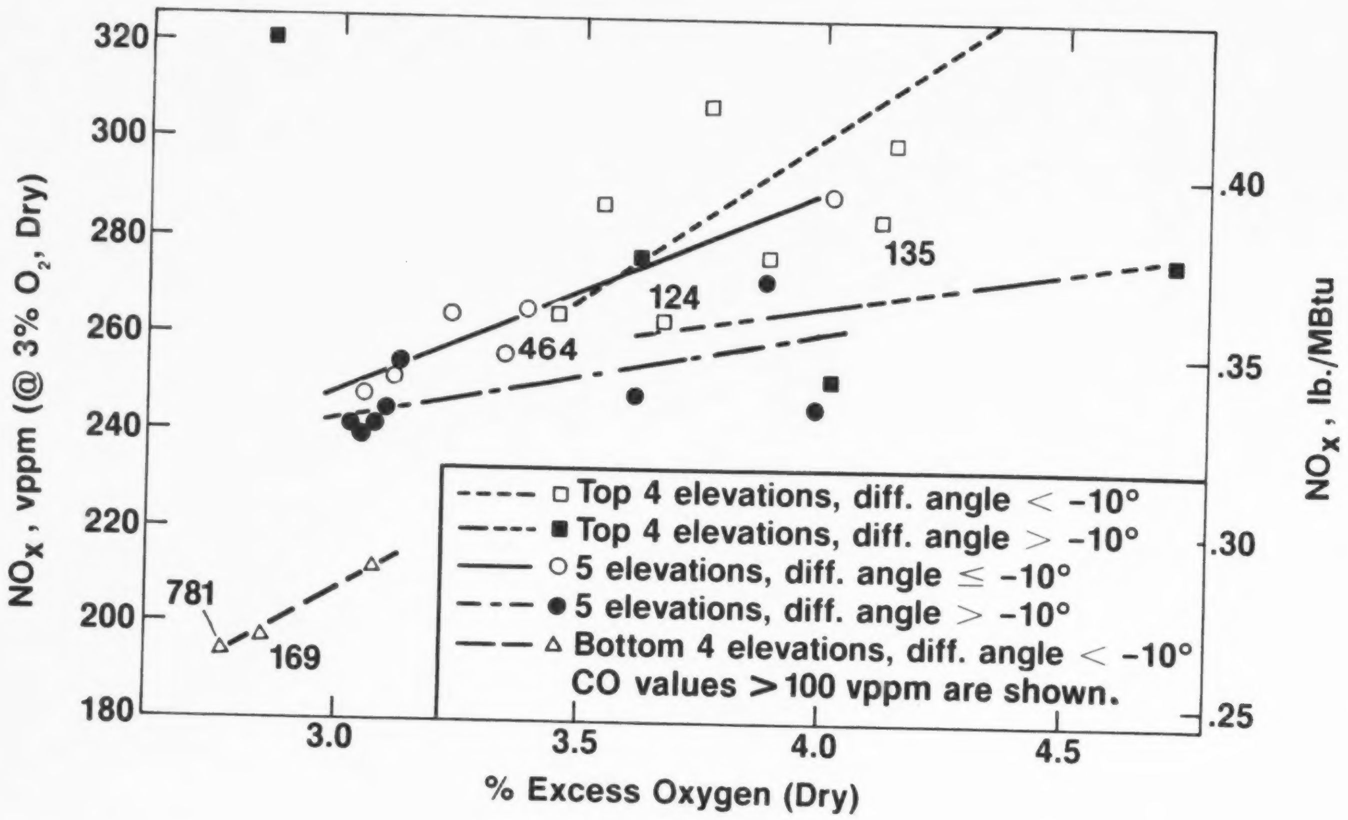

Figure D-24
Effect of Fuel Elevations in Service on NO_X Levels
(Minimal Staging, Modification 2 Tests)

TABLE D-24 (PG 1 OF 2)
DATA FOR FIGURE D-24
EFFECT OF FUEL ELEVATIONS IN SERVICE ON NOx LEVELS
(MINIMAL STAGING, MODIFICATION 2 TESTS)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT 02	NOX VPPM	CO VPPM	NOTES
Top 4 Elevations, Differential Angle Less Than -10 Degrees															
522	320	4	100	4.5	70	8	0	15	5	40	5	4.15	300	26	1
523	320	4	100	4.5	70	8	0	19	5	40	5	4.26	321	58	1
525	320	4	100	4.5	70	8	10	23	2	40	2	4.12	284	135	1
526	320	4	100	4.5	70	8	10	18	2	40	2	3.61	275	32	1
535	321	4	100	4.0	100	8	10	25	0	40	0	3.76	305	36	1,2
536	317	4	100	4.6	50	8	10	23	0	40	0	3.55	287	27	1,2
543	320	4	100	4.4	50	8	10	23	5	40	5	3.87	275	37	1
544	321	4	100	4.3	50	8	10	23	3	40	3	3.45	264	65	1
545	320	4	100	4.3	50	8	10	23	2	40	2	3.67	263	124	1
Top 4 Elevations, Differential Angle Greater Than -10 Degrees															
384	335	4	90	4.5	100	8	0	7	10	50	10	4.01	251	50	
527	320	4	100	4.5	70	8	10	13	8	40	8	4.74	277	17	1
5 Elevations, Differential Angle Less Than Or Equal To -10 Degrees															
357	337	5	70	4.5	48	17	0	12	14	50	14	3.34	254	464	3
374	322	5	90	4.0	100	8	0	20	0	50	0	4.02	288	88	
504	320	5	100	3.1	100	8	10	20	0	50	0	3.05	247	19	1
505	320	5	100	3.4	100	8	10	17	0	50	0	3.02	241	21	1
506	320	5	100	3.3	100	8	10	16	0	50	0	3.07	241	24	1
507	321	5	100	3.2	100	8	10	15	0	50	0	3.05	239	27	1
508	320	5	100	3.0	100	8	10	18	0	50	0	3.12	254	21	1
509	310	5	100	2.5	100	8	10	19	0	50	0	3.09	244	22	1
537	314	5	100	3.4	50	8	10	24	0	40	0	3.11	251	31	1
538	314	5	100	2.8	100	8	10	23	0	40	0	3.39	265	22	1
542	325	5	100	4.5	50	8	10	23	1	40	1	3.23	264	50	1
5 Elevations, Differential Angle Greater Than - 10 Degrees															
369	331	5	90	4.5	100	17	0	8	0	50	0	3.88	270	82	3
513	327	5	100	4.0	100	8	10	14	0	0	0	3.28	232	44	1
514	326	5	100	3.7	100	8	10	13	0	100	0	3.61	248	28	1
517	326	5	100	4.1	100	8	10	9	0	40	0	4.00	245	24	1

TABLE D-24 (PG 2 OF 2)
DATA FOR FIGURE D-24
EFFECT OF FUEL ELEVATIONS IN SERVICE ON NOx LEVELS
(MINIMAL STAGING, MODIFICATION 2 TESTS)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT 02	NOX VPPM	CO VPPM	NOTES
Bottom 4 Elevations, Differential Angle Less Than -22 Degrees															
539	310	4	100	4.1	100	8	10	23	0	40	0	3.06	212	55	1,4
540	313	4	100	4.0	50	8	10	22	0	40	0	2.84	198	169	1,4,5
541	314	4	100	4.1	50	8	10	22	0	40	0	2.77	195	781	1,4,5

Notes:

1. Left front burners on elevations 4 and 5, and the right rear burner on elevation 5 were at horizontal orientations (0 degrees) due to broken linkages.
2. Primary air was flowing through the elevation 5 burners in anticipation of a load (and mill) increase.
3. Large oxygen imbalance.
4. Bottom 4 fuel elevations in operation.
5. Oxygen and CO concentrations fluctuated drastically during these tests.

practiced, due to difficulty in controlling boiler temperatures. Also shown in the figure are results from 5 fuel elevation and top 4 fuel elevation tests conducted at slightly greater differential angles (i.e., > -10°). Again, these results indicate similar NO_x levels for 5 fuel elevation and top 4 fuel elevation services.

The above results indicate that in the 280 to 330 MW_e load range, the choice of fuel elevations in service should be based on boiler considerations other than NO_x reductions because there is no apparent NO_x reduction benefit when comparing 5 fuel elvations with top 4 fuel elevations. Although similar tests were not performed for the 180 to 220 MW_e load range, the same argument may apply for middle 3 fuel elevations versus top 4 fuel elevations, but this would require confirmation (e.g., limited testing by UP&L).

H. Effects of Fuel Air Damper Position, Windbox-Furnace Differential Pressure and Lower Auxiliary Air Compartment Settings on NO_x Levels

The effect of fuel air damper position on NO_x levels is shown in Figure D-25. The data are listed in Table D-25. Because NO_x variations with damper position were subtle, NO_x levels have been normalized to correct for varying excess oxygen levels, and only sequential test results were compared. From the figure, on the average, one can see that the fuel air damper settings versus normalized NO_x levels followed a characteristic pattern. The pattern shows modest normalized NO_x decreases (equivalent to ~ 30 vppm) as fuel air dampers are changed from 100% open down to 20% open. Additional decreases (equivalent to ~20 vppm) were seen from 20% open down to 10% open. In comparing baseline and Modification 1 results, baseline tests showed a 50 vppm NO_x decrease as fuel air damper

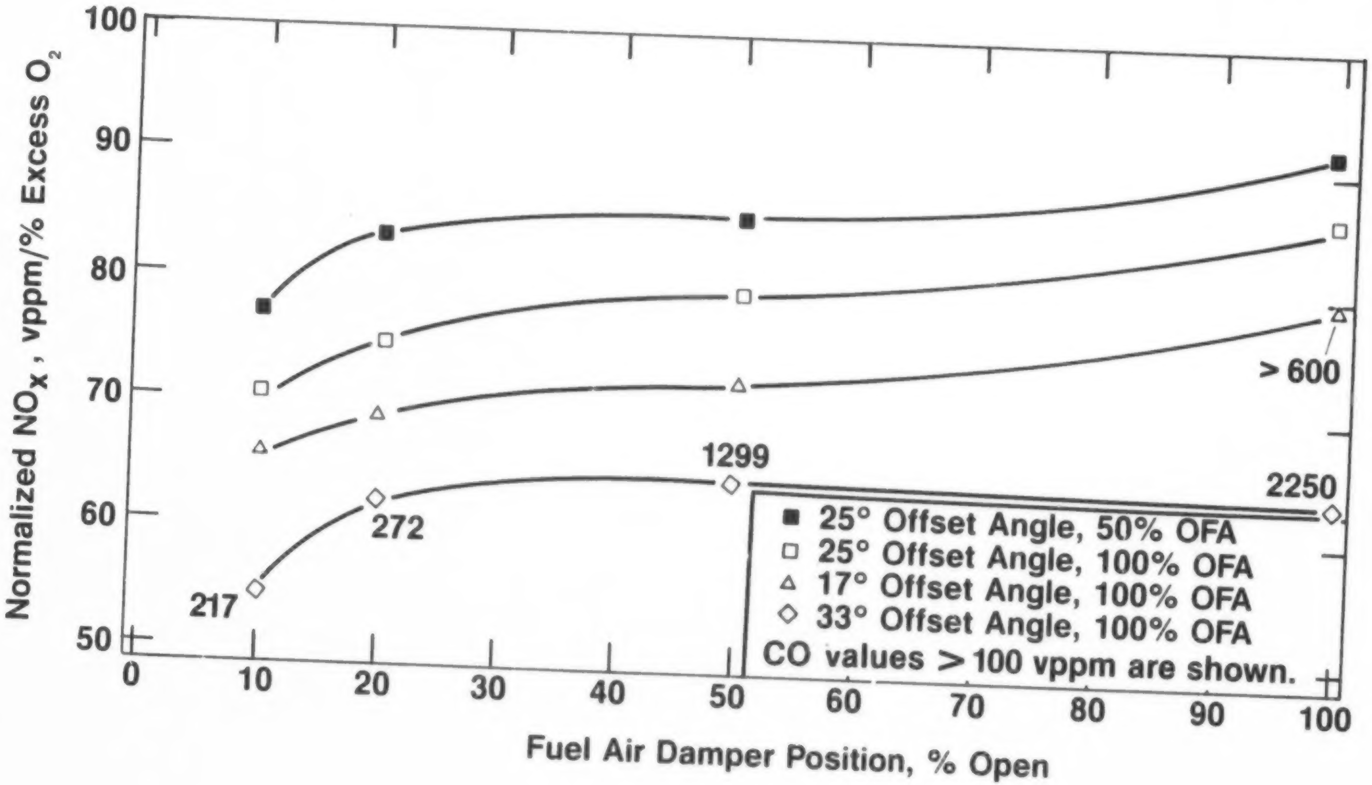

Figure D-25
Effect of Fuel Air Damper Positions on NO_x Levels

1084-3-350

TABLE D-25
DATA FOR FIGURE D-25
EFFECT OF FUEL AIR DAMPER POSITIONS ON NOx LEVELS
(ALL 5 FUEL ELEVATIONS IN USE)

TEST NO.	MWE GROS	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	NORMALIZED(2) NOx	CO VPPM	NOTE
25 Degree Offset Angle, 50% Overfire Air															
209	425	100	5.4	50	25	0	0	44	0	0	3.55	325	91.6	66	
210	422	50	5.5	50	25	0	0	45	0	0	3.65	311	85.2	31	
211	420	20	5.4	50	25	0	0	51	0	0	3.67	307	83.7	17	
212	414	10	5.3	50	25	0	0	60	0	0	3.90	300	76.9	22	
25 Degree Offset Angle, 100% Overfire Air															
202	428	100	5.6	100	25	0	0	45	0	0	3.79	327	86.3	32	
203	427	50	5.3	100	25	0	0	47	0	0	4.08	323	79.2	34	
204	418	20	5.6	100	25	0	0	49	0	0	4.14	309	74.6	14	
205	414	10	5.5	100	25	0	0	56	0	0	4.21	296	70.3	11	
17 Degree Offset Angle, 100% Overfire Air															
231	417	10	5.3	100	17	0	0	52	0	0	4.38	287	65.5	31	
232	422	20	5.4	100	17	0	0	46	0	0	4.29	296	69.0	20	
233	428	50	5.2	100	17	0	0	39	0	0	4.08	295	72.3	90	
234	427	100	5.5	100	17	0	0	36	0	0	3.37	270	80.1	>626	1
33 Degree Offset Angle, 100% Overfire Air															
246	411	100	5.3	100	33	0	0	35	0	0	4.03	256	63.5	2250	
247	410	50	5.4	100	33	0	0	36	0	0	4.19	269	64.2	1299	
248	412	20	5.4	100	33	0	0	40	0	0	4.30	266	61.9	272	
249	410	10	5.2	100	33	0	0	47	0	0	4.78	260	54.4	217	

Notes:

1. CO scale not properly set for one of the probe assemblies; therefore, a > symbol has been added.
2. Normalized NOx in vppm per % excess oxygen (dry).

positions were reduced from fully open to 50% open. Similarly, Modification 1 demonstrated NO_x reductions equivalent to 20 vppm (based on normalized NO_x levels) for this same reduction in fuel air damper position. However, fuel air damper settings of $\leq$20% open are undesirable due to flame instability.

In general, the Modification 1 NO_x reductions due to fuel air damper setting decreases were less than those seen during the baseline testing. This is because the Modification 1 hardware changes had already reduced the free area in the fuel air compartments significantly. Because of the resulting lower flows, closing down the dampers had less effect than was previously seen.

The effect of windbox-furnace differential pressure (ΔP) on NO_x levels is shown in Figures D-26 and D-27 which show NO_x vs excess O_2 for several ΔP's and other parameters. The data for these figures are listed in Tables D-26 and D-27, respectively. Increased windbox-furnace pressure differences cause higher air velocities through the offset angle turning vanes and may increase their effectiveness in decreasing NO_x emissions. Figure D-26 shows average staging tests conducted during Modification 1 with offset angles at 17° and 25° with normal and slightly lower than normal differential pressures. Results indicate a negligible effect of differential pressure on NO_x levels at both offset angles. In Figure D-27, deep staging Modification 2 tests were performed. One test, which was run at a very high differential pressure (9.0 inches w.g.) indicated a definite NO_x reduction when compared with the normal (~5.5 inches w.g.) differential pressure tests. However, operation of the boiler at such a high differential pressure in order to achieve modest (~30 vppm) NO_x reductions is not desirable. This is because of the higher power required by the forced draft fans, which would decrease overall plant effi-

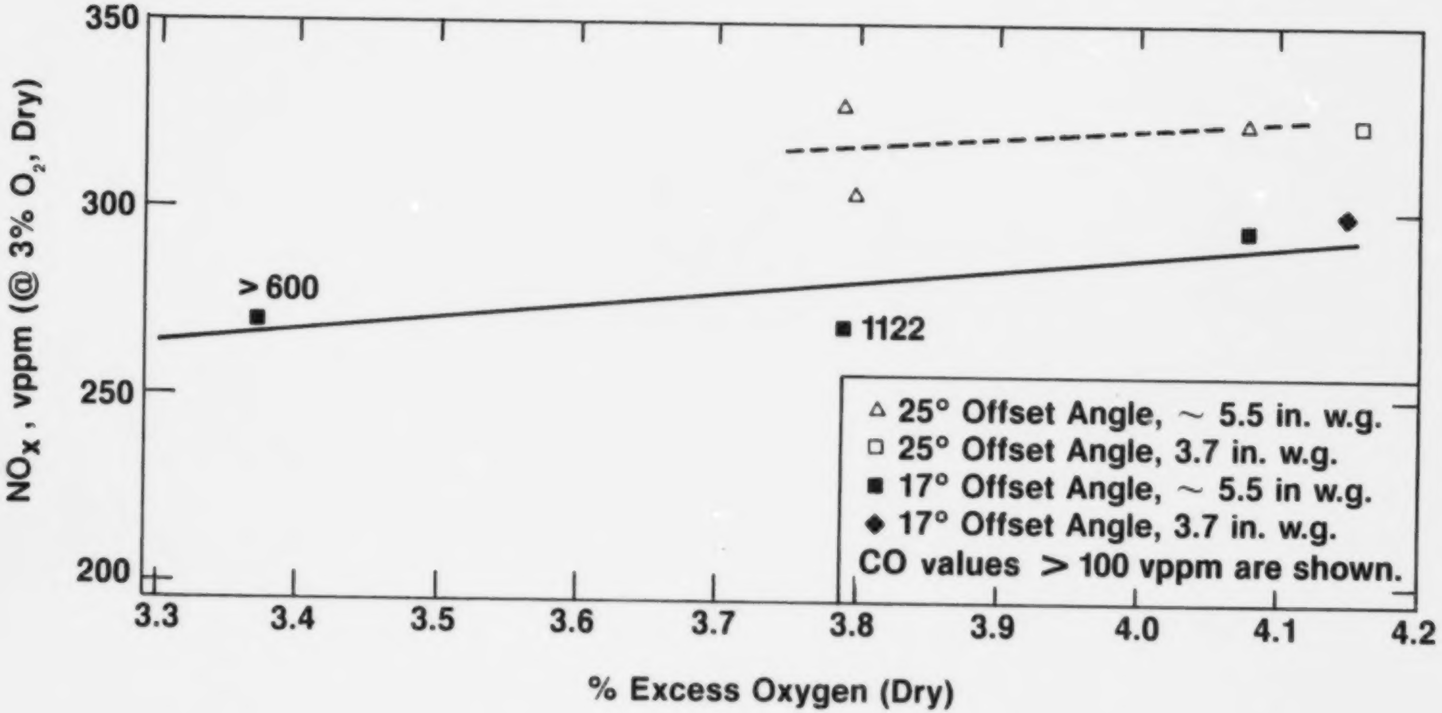

Figure D-26
Effect of Windbox/Furnace Differential Pressure
on NO$_X$ vs O$_2$ Levels for Various Offset Angles
(Overfire Air Operation)

TABLE D-26
DATA FOR FIGURE D-26
EFFECT OF WINDBOX/FURNACE DIFFERENTIAL PRESSURE ON NOx LEVELS FOR VARIOUS OFFSET ANGLES (OVERFIRE AIR OPERATION)

TEST NO.	MWE GROSS	ELEV •	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM	NOTES
202	428	5	100	5.6	100	25	0	0	45	0	0	3.79	327	32	
203	427	5	50	5.3	100	25	0	0	47	0	0	4.08	323	34	
206	419	5	100	3.7	100	25	0	0	70	0	0	4.16	323	18	
207	424	5	100	5.2	100	25	0	0	42	0	0	3.80	303	68	
233	428	5	50	5.2	100	17	0	0	39	0	0	4.08	295	90	
234	427	5	100	5.5	100	17	0	0	36	0	0	3.37	270	>626	1
235	421	5	100	3.7	100	17	0	0	60	0	0	4.15	299	37	
236	420	5	100	5.4	100	17	0	0	35	0	0	3.79	268	1122	

NOTE:

1. CO scale not properly set for one of the probe assemblies; therefore, a > symbol has been added.

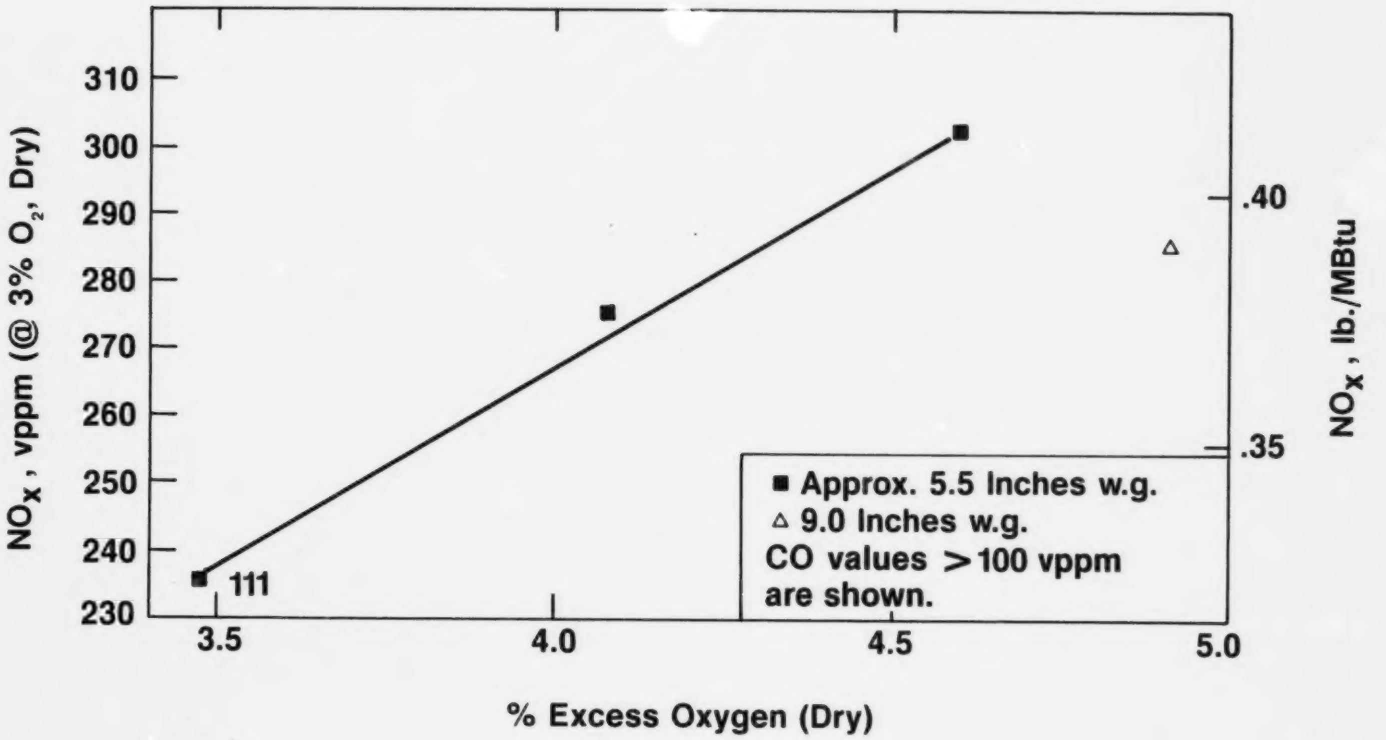

Figure D-27
Effect of Windbox/Furnace Differential Pressure
on NO$_X$ vs O$_2$ Levels
(Overfire Air Operation)

TABLE D-27
DATA FOR FIGURE D-27
EFFECT OF WINDBOX/FURNACE DIFFERENTIAL PRESSURE ON NOx VS O2 LEVELS
(OVERFIRE AIR OPERATION)

TEST NO.	MWE GROSS	ELEV	FAD	DELTA_P	OFAD	OFF-SET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX VPPM	CO VPPM
331	427	5	100	5.5	100	17	30	-15	28	50	28	3.47	236	111
332	427	5	100	5.5	100	17	30	-15	27	50	27	4.60	302	29
333	428	5	100	9.0	100	17	30	-15	17	50	17	4.91	285	25
334	430	5	100	6.0	100	17	30	-15	26	50	26	4.08	276	43

ciency. Also, these high fan powers could not be sustained in long term operation without significant redesign.

The effect of lower auxiliary air compartment settings (compartments Aux 5 and Aux 4-5) on NO_x levels was evaluated throughout the various post-modification phases. Basically, it appears that operation of these compartments does not have much of a direct effect on NO_x levels. Instead, there seems to be an indirect effect through their influence on both inter-duct and intra-duct oxygen imbalances. At times, major adjustments of the lower auxiliary air compartment damper settings had no apparent effect on NO_x levels. However, at other times, minor adjustments significantly aggravated the oxygen imbalances and subsequently, affected NO_x levels. Because use of the lower auxiliary air compartments often affected intra-duct oxygen imbalances, CO levels were very susceptible to compartment operations. Evidently, operation of the lower auxiliary air compartments is another factor which adds to the complexity of the boiler aerodynamics.

III. OVERALL DATA COMPILATION, TESTING SUMMARY AND CONCLUSIONS

A. Overall Data Compilation

In Figure D-28, post modification test results are shown for those low-NO_x conditions which are considered easy to implement. These conditions include the following:

- For loads <280 MW_e, the lowest possible excess oxygen levels (without affecting boiler operability) should be maintained.
- For loads $\geq$280 MW_e, excess oxygen levels should be maintained at $\leq$ 4.5%.

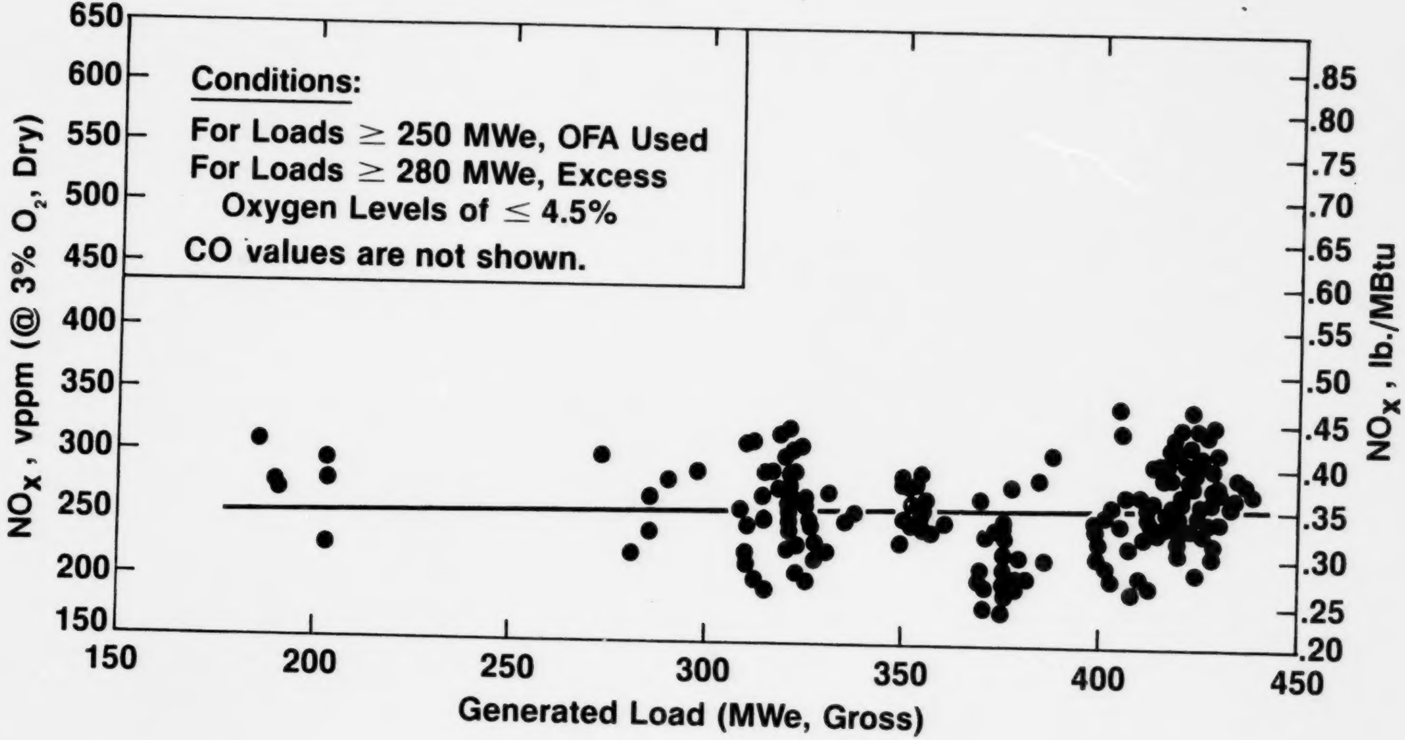

Figure D-28
NO$_X$ Levels as a Function of Load for Short-Term, Post-Modification Tests

1084-4-432

- For loads $\geq$250 MW_e, overfire air should be used.

However, it can be seen that restricting boiler operations by instituting the above three constraints was still not effective enough to prevent high CO levels in some of tests run at >300 MW_e.

In Figure D-28, a linear regression line drawn through the data points indicates that over the entire range of operating loads, the average NO_x emission rate was f265 vppm (~0.36 lb/ MBtu, 155ng/J) and ranged from 179 vppm (0.25 lb/MBtu, 105 ng/J) to 344 vppm (0.47 lb/MBtu, 200 ng/J) during these short term tests. This average value is only about 12% less than the average of 0.41 lb/MBtu (305 vppm, 176 ng/J) seen in the four long-term 30-day CEM tests performed during Modification 2 (see Part E).

The manual and automatic boiler controls are the key to operating Hunter No. 2 at the lowest possible NO_x levels (without incurring high CO levels). Most of the controls on this boiler perform automatically to ensure boiler stability while leaving adequate flexibility for the skilled operators to handle upsets in the manual mode. Because of the complex aerodynamics of this boiler, it was sometimes difficult to restore stability following certain types of upsets. For example, adjusting the burner tilts to correct a steam temperature problem often resulted in long lasting oxygen imbalance between the two flue gas exhaust ducts. Therefore, because the automatic excess air control was set to monitor which ever duct had the lower O_2 reading (rather than the average), the original steam temperature upset could cause increased total excess air and thus increased NO_x for up to an hour after the original steam temperature problem has been corrected.

Similarly, the operational adjustments required to handle other types of small upsets could increase NO_x levels somewhat and these slightly increased emissions could continue for sometime even after the original problem has been corrected. The control of an upset and the quick return to stable low-NO_x conditions can be a rigorous and demanding task at which many of the Hunter control board operator have demonstrated remarkable proficiency.

In addition to using manual controls, the control board operator's role in maintaining stable boiler operation and/or low NO_x conditions might have been aided by the installation of certain additional automatic controls. These automatic controls could include automatic overfire air damper controls, and overfire air compartment tilt controls. Automatic overfire air damper control, as a function of load, was suggested during the test program, but because the test data were still preliminary at that point, automation of the OFA dampers was not performed. Automation of the overfire air compartment tilt controls would have required extensive hardware modifications and was thus also not performed.

Unstable boiler operations (e.g., large oxygen imbalances) often occurred at deep to moderate staging conditions. This could be corrected by adjusting the burner tilts. However, this action often affected other boiler controls. An alternative would to manually adjust the overfire air compartment tilts. In the absence of a remote controller, this was a difficult task, and was usually not performed.

B. Summary of Parametric Effects on NO_x Reductions and Recommended Operating Conditions

The results of the post-modification tests of parametric NO_x reduction techniques are summarized in Table D-28. The large variability in NO_x reduction trends shown in the table demonstrate that the effects of the various operating parameters at the modified Hunter No. 2 Unit are interrelated. In addition, a comparison of the post-modification results with baseline test results is shown in Table D-29. Clearly, the boiler modifications had a significant effect on reducing NO_x levels.

One topic which has been discussed at length throughout Part D, Section II is boiler instability (e.g., oxygen imbalances and associated high CO levels). To sum up this condition, the oxygen imbalance was initially present at the Hunter No. 2 Unit. However, the boiler modifications (both hardware and operational) aggravated the oxygen imbalance at certain operating conditions. Also, the increased complexity of the boiler aerodynamics created by the boiler modifications made it difficult to predict most conditions under which large imbalances would occur. Eventually though, many of the control board operators became familiar with the appearance of the imbalance and became proficient at minimizing it.

The solution to the oxygen imbalance problem is to operate the boiler under the low-NO_x conditions specified in Table D-30, and then to inventory the range of operating conditions under which the imbalances usually occur. Boiler operation may then be modified to avoid these conditions. If imbalance conditions still arise, they may be minimized by employing techniques learned by experienced control board operators. Additionally, the oxygen imbalance conditions could be better controlled by automating the overfire air damper setting (as a function of

TABLE D-28

(p.1 of 2)

POST-MODIFICATION TESTING
NO_x REDUCTION LEVELS FOR VARIOUS OPERATING PARAMETERS
(REDUCTIONS IN VPPM)

	(1) Load MW_e	(2) Offset Angle	Non-OFA	(3) OFA Staging	Modification Phase M1	M2	M1 & M2	M3
1. **Excess Oxygen**								
- NO_x reductions per 1% decrease in excess oxygen levels (down to ~2.5% oxygen)	Full	-	✓	-	-	-	60	-
	Full	-	-	A to M	-	-	60	-
	Full	-	-	D	-	-	50	-
	~380	-	-	D	-	-	50	-
	~300	8	✓	-	-	50	-	-
	Full	25	-	M	18	-	-	-
	Full	17	-	M	28	-	-	-
	Full	33	-	M	76	-	-	-
	Full	25	-	D	85	-	-	-
	Full	17	-	D	35	-	-	-
	Full	17	-	D	-	50	-	-
	Full	33	-	D	-	55	-	-
	~300	8	✓	-	-	-	-	45
2. **Windbox Modifications Plus Overfire Air**								
• **Modification 1**								
- NO_x reductions compared to non-OFA baseline tests	Full	-	✓	-	0	-	-	-
- NO_x reductions compared to non-OFA baseline tests	Full	-	-	A to M	140	-	-	-
- NO_x reductions compared to OFA baseline tests	Full	-	-	A to M	60	-	-	-
- NO_x reductions compared to OFA baseline tests	Full	-	-	M	40	-	-	-
- NO_x reductions compared to OFA baseline tests	Full	-	-	A	50	-	-	-
• **Modification 2**								
- NO_x reductions compared to non-OFA baseline tests	Full	-	✓	-	-	80	-	-
- NO_x reductions compared to non-OFA baseline tests	~300	8	✓	-	-	110	-	-
- NO_x reductions compared to OFA Modification 1 tests	Full	-	-	M	-	40	-	-
- NO_x reductions compared to OFA Modification 1 tests	Full	-	-	D	-	0	-	-
• **Modification 3**								
- NO_x reductions compared to non-OFA baseline tests	~300	8	-	-	-	-	-	70
- NO_x increasess compared to non-OFA Modification 2 tests	~300	8	✓	-	-	-	-	40
3. **Burner (Nozzle) Tilt**								
- NO_x reductions per 10° burner tilt increase	~315	8	✓	-	-	20	-	-
4. **Differential Angle** (i.e., the angle between the overfire air compartments and the fuel compartments)								
- NO_x reductions per 30° increase in differential angle	Full	25	-	CL	≤40	-	-	-
	315/350/370	8	-	CL	-	≥75	-	-
	~300	8	-	CL	-	-	-	70

TABLE D-28
(p. 2 of 2)

POST-MODIFICATION TESTING
NO_x REDUCTION LEVELS FOR VARIOUS OPERATING PARAMETERS
(REDUCTIONS IN VPPM)

(CONTINUED)

5. Fuel Air Damper Position
   - Slight NO_x decreases of ~30 vppm for fuel air damper position reductions from 100% open to 20% open, then additional NO_x decreases of ~20 vppm for reductions from 20% open down to 10% open

6. Load
   - Consistent NO_x levels over the load range from ~280 ME_e to full load, except for a slight NO_x decrease of ~25 vppm in the load range 370 MW_e to 390 MW_e.

7. LNCFS Offset Angle
   - Sensivity to excess oxygen changes shown above. Sensitivities to excess oxygen levels and relative effects on NO_x levels varied significantly with other operating parameters.

8. Windbox/Furnace Differential Pressure
   - Increase from 3.7 inches w.g. to 5.5 inches w.g. produced no apparent NO_x changes, but an increase from 5.5 inches w.g. to 9.0 inches w.g. decreased NO_x levels ~30 vppm.

9. Lower Auxiliary Air Compartment Settings
   - No direct effect on NO_x levels. Indirect effect through relationship with boiler stability parameters.

Notes:

(1) Full load is the range from approximately 395 MW_e to 430 MW_e.
(2) Offset angles are shown only for those data sets with constant values.
(3) The degrees of overfire air staging are defined as follows:

A - average staging, i.e., differential angles of 0° ±5°
M - moderate staging, i.e., differential angles of 30° ±5°
D - deep staging, i.e., differential angles of $\geq 40°$
CL - changing levels of angle differentials

TABLE D-29

POST-MODIFICATION VERSUS BASELINE CHARACTERIZATION TESTING NO_x REDUCTION LEVELS FOR VARIOUS OPERATING PARAMETERS (REDUCTIONS IN VPPM)

		Modification Phase		
	Baseline	M1	M2	M3
1. Excess Oxygen - NO_x reductions per 1% decrease in excess oxygen levels (down to 2.5% excess oxygen)	60 (50-70)	---- 55 (18-85) ----		45
2. Windbox Modifications - NO_x reductions compared to non-OFA baseline conditions	-	0	95 (80-110)	70
3. Overfire Air Plus Windbox Modifications - NO_x reductions compared to non-OFA baseline conditions	90 (75-105)	140*	≥ 140	-
4. Burner (Nozzle) Tilt - NO_x changes per 10° increase in burner tilt	+25	-	-20	-
5. Differential Angle (i.e., the angle between the overfire air compartments and the fuel compartments) - NO_x reductions per 30° increase in differential angle	≤ 30	≤ 40	≥ 75	70
6. Fuel Air Damper Positions - NO_x reductions for decreases from fully open position to 50% open	50	20	-	-

*Distinct synergistic effect

load) and by automating the overfire air compartment tilt controls.

As stated consistently throughout Part D, the operational and hardware modifications instituted in this test program increased the complexity of boiler operation and increased the parametric interrelationship between NO_x reductions and boiler stability. In response, Table D-30 suggests optimum operating conditions, taking into account NO_x minimization and boiler stability, and also allowing the flexibility needed for the control board operators to test and determine some of the operating parameters.

C. Conclusion

NO_x levels during standard full load operating conditions (i.e., 4.5% excess oxygen, no overfire air, and burner tilts of 0° ±5°) prior to the institution of NO_x reduction techniques (both hardware and operational) were about 460 vppm (~0.63 lb/MBtu, 271 ng/J). These levels were effectively reduced through the use of combustion modifications, as summarized in Tables D-28 and D-29.

During several short term post-modification tests, NO_x levels of 180 to 200 vppm (0.25 to 0.27 lb/MBtu, 108 to 116 ng/J) were achieved at slightly less than full load by using extreme low-NO_x conditions (not recommended for long term operation). These levels demonstrate a potential reduction of approximately 60% over standard full load operation for boilers that are able to run routinely under the special conditions of these tests. A review of the test data indicate that about half of this reduction is attributed to the combination of overfire air usage plus windbox modifications and the remainder of the reduction is split between excess air and other effects.

TABLE D-30

SUMMARY AND RECOMMENDATIONS OF BOILER OPERATING CONDITIONS AT THE HUNTER NO. 2 UNIT

- Overfire Air - shows a significant effect on decreasing NO_x. An overfire air versus load profile, as shown in Figure D-23 should be employed. This profile could be programmed into the boiler's automatic controls.

- Modifications - Modification 2 showed the greatest NO_x reduction potential, but also the greatest degree of instability. Therefore, either Modification 3 or Modification 1 are suggested since each sacrifices a modest degree of NO_x reduction potential for increased boiler stability. Further testing would be required before choosing between Modification 3 and Modification 1.

- LNCFS Offset Angle - although large offset angles (≤17") had a definite effect on reducing NO_x levels, these effects varied significantly with other operating parameters. Since large offset angles increased the complexity of the boiler aerodynamics, they contributed to boiler instability. Offset angles, of ≤8° are recommended since these levels will maintain boiler stability while only sacrificing a modest degree of NO_x reduction potential.

- Burner (Nozzle) Tilts - burner (nozzle) tilts for non-overfire air operation (i.e., less than about 230 to 250 MW_e) will automatically be in the extreme uptilt position (about +10° to +30°). Since the boiler modifications reversed the baseline NO_x versus burner tilt trend such that NO_x levels decrease with increasing burner tilts, the burner tilts should be kept on automatic control.

- Differential Angle - maximum levels should be attempted without effecting large interduct oxygen imbalances (i.e. >1.0% difference). These levels should be determined by the control board operators. For less than ~280 MW_e operation, these angles most probably would have to be decreased considerably. Automation of the overfire air compartment tilts would aid in controlling oxygen imbalances. Eventually, a programmable overfire air tilt versus burner tilt and load profile could be developed.

- Fuel Air Damper Settings - since large reductions in fuel air damper settings down to unacceptably low levels are required to achieve slight NO_x reductions, fuel air damper settings should be kept on automatic.

- Windbox/Furnace Differential Pressure - since large increases in differential pressures up to unacceptably high levels are required to achieve modest NO_x reductions, differential pressures should be maintained at their current automatic levels.

- Lower Auxiliary Air Compartment Operation - since opertion of the two lower elevations of auxiliary air compartments showed no direct effect on NO_x levels, it is recommended that the Aux. 5 (bottom auxiliary) compartment be maintained at a moderate level, e.g. 25% open, and the Aux. 4-5 (oil gun auxiliary) compartment be kept on automatic (i.e., in synch with the other elevations of auxiliary air compartments.

- Oxygen Imbalance Control - the oxygen imbalance condition was reduced with the installation of Modification 3. However, the control board operators should continue to monitor those conditions which still cause a significant imbalance, and update (then apply) their techniques for reducing the imbalance. Automation of the overfire air compartment tilts would aid in controlling the oxygen imbalance.

A breakdown of the parametric contributions to this reduction follows. NO_x may be decreased by ~80 vppm (18%) for excess oxygen reductions from 4.5-5.0% to 3.0-3.5%. NO_x may be decreased by ~140 vppm (31%) by the use of overfire air (at average to moderate degrees of staging) under either Modifications 1 or 2. NO_x may be decreased by ~50 vppm (11%) by additional parametric effects including deep staging, LNCFS offset angles of $\geq$17°, and slightly reduced load. Further, these levels fulfilled the short term, full load, optimized performance goal of 0.30 lb/MBtu (129 ng/J) for this boiler. The levels appear to be approaching a low-NO_x threshhold for this type of boiler, fuel type, and fuel system design.

Over the entire range of boiler operations, the short term tests demonstrated the ability to achieve average NO_x levels of about 265 vppm (0.36 lb/MBtu, 155 ng/J). However, this average was achieved by using an exceptional degree of manual boiler control. In the future, some of these controls (e.g. OFA dampers settings) could be automated and programmed (e.g., load following) to assist boiler operators in achieving optimum low-NO_x operation. In comparison, an average NO_x level of 0.41 lb/MBtu (176 ng/J) was demonstrated in the four 30-day CEM tests (see Part E), which incorporated a more modest (typical) degree of boiler control during Modification 2.

PART E

THIRTY-DAY CONTINUOUS MONITORING OF FLUE GAS EMISSIONS

I. PURPOSE OF THE THIRTY-DAY TESTS

Four thirty-day tests were performed with two goals in mind:

- To quantify flue gas emissions during normal load patterns over a period long enough to be representative of long-term operation.
- To evaluate the ability of continuous emission monitors (CEMs) to perform within the EPA's performance specifications for such monitors.

To these ends, a continuous record of 15-minute emission averages (CO, CO_2, O_2, and NO_x) was logged concurrently with boiler operating data over each of the 30-day periods. Also, the continuous emission monitors (CEM) were evaluated for quality and for compliance with EPA performance specifications PS2[E1] (for SO_2 and NO_x monitors) and PS3[E1] (for CO_2 and O_2 monitors). This evaluation included several measurements of drift, accuracy, precision (repeatability), and response time.

II. EXPERIMENTAL PROCEDURES FOR THE 30-DAY TESTS

The four 30-day tests were performed on the Hunter boiler (Oct.-Dec. 1982, April-May 1983, June-July 1983, and July-Aug. 1983) by KVB, Inc. under subcontract to ER&E. All four tests were performed while the boiler was operating with the Modification 2 hardware in place. During these tests, UP&L agreed to operate the boiler (overfire air and total excess air) as closely as possible to the recommened operating profiles shown in Figure D-23. During each test, boiler load was recorded along with a semi-continuous (once every four seconds) record of stack emissions. Also, at periodic intervals, the performance (response time, accuracy, zero and span drift, etc.) of each continuous emission monitor was evaluated according to EPA procedures. The sampling and analysis methods were similar to those described in Part B, Section I of this report. A more detailed description of the experimental procedures used for the 30-day tests may be found in Appendix V.*

III. RESULTS AND DISCUSSION OF THE 30-DAY TESTS

A. Continuous Monitor Certification Tests

During the 30-day test periods, the continuous monitor system described above was used to measure the boiler's gaseous emissions. Following shipment to the test site, the monitoring system was installed, and certification tests were performed according to EPA's Performance Specifications 2, and 3 (PS2 and PS3), 40 CFR 60.[E1]

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*It should be noted that only the NO concentrations (as opposed to NO + NO_2) were measured during the 30 day testing. This was necessitated because: (1) added complexity in the sampling system (heated lines and more sophisticated controllers) would have been necessary, and (2) typically the NO_2 component of the total NO_x is a small percentage (<5%) and it was decided (with EPA concurrence) that NO measurement would be satisfactory.

These specifications establish minimum performance criteria that the monitoring system must meet in terms of eight parameters: accuracy, calibration error, two- and 24-hour zero drifts, two- and 24-hour calibration drifts, response time, and operational period.

The raw data for the CEM performance certification tests are too voluminous for presentation here. However, those data, and the performance of the continuous monitor system are summarized in Table E-1. All performance values are in percentage of the span value. Also shown in the table are the monitor specifications extracted from PS2 and PS3. The performance of the CO analyzer, which was not covered by a formal performance specification, is also included on the table. (The CO analyzer was used to monitor the combustion conditions in the boiler because it is a very sensitive indicator of combustion performance.) Table E-1 shows that each analyzer in the continuous monitor system performed better in all categories (accuracy, drift, etc.) than is required by the EPA performance specifications.)

B. Gaseous Emissions Test Results

Summaries of the 24-hour averages for the 30-day test periods are presented in Tables E-2, E-3, E-4, and E-5. As an example, a partial listing of the 15-minute averages, from which the 24-hour averages were compiled, may be found at the end of Appendix V.

A statistical analysis of the data was performed to determine the distribution characteristic of the 24-hour averages and to calculate statistical parameters. The normal distribution statistical parameters are presented in Table E-6 for all the 24-hour averages, and show, for Test 2, for example, that the

TABLE E-1 INSTRUMENT SPECIFICATIONS AND PERFORMANCE

Parameter	EPA Performance Specifications	Actual Performance 1st Test	2nd Test	3rd Test	4th Test
THERMO ELECTRON SERIES 10 NO_x ANALYZER					
• Accuracy	≤ 20 % of mean ref. value	4.1%	6.0%	6.15%	4.46%
• Calibration error mid	≤ 5% of cal gas value	0.27%	0.4%	0.30%	0.88%
high	≤ 5% of cal gas value	0.38%	0.64%	0.29%	0.36%
• Zero drift (2 hour)	2% of span	0.0014%	0.64%	0.29%	0%
• Zero drift (24 hour)	2% of span	0%	0%	0%	0%
• Calibration drift (2 hour)	2% of span	0.25%	0.097%	0.16%	0.48%
• Calibration drift (24 drift)	2.5% of span	0.34%	0.27%	0.20%	0.25%
• Response time	15 minute maximum	55 sec	53 sec	54 sec	52 sec
• Operational period	168 hour minimum	720 hr	720 hr	720 hr	720 hr
HORIBA INSTRUMENTS PIR 2000 CO_2 ANALYZER					
• Zero drift (2 hour)	≤ 0.4 pct CO_2	0%	0%	0%	0%
• Zero drift (24 hour)	≤ 0.5 pct CO_2	0%	0%	0%	0%
• Calibration drift (2 hr)	≤ 0.4 pct CO_2	0.021%	0.049%	0.040%	0.3%
• Calibration drift (24 hr)	≤ 0.5 pct CO_2	0.14%	0.049%	0.07%	0.28%
• Response time	10 minute maximum	61 sec	60 sec	55 sec	61 sec
• Operational period	168 hour minimum	720 hr	720 hr	720 hr	720 hr
THERMOX MODEL III O_2 ANALYZER					
• Zero drift (2 hour)	≤ 0.4 pct O_2	0%	0%	0%	0%
• Zero drift (24 hour)	≤ 0.5 pct O_2	0%	0%	0%	0%
• Calibration drift (2 hour)	≤ 0.4 pct O_2	0%	0%	0.04%	0.03%
• Calibration drift (24 hr)	≤ 0.5 pct O_2	0%	0%	0.04%	0.02%
• Response time	10 minute maximum	70 sec	75 sec	61 sec	70 sec
• Operational period	168 hour minimum	720 hr	720 hr	720 hr	720 hr
HORIBA INSTRUMENTS PIR 2000 CO ANALYZER					
• Calibration error mid	≤ 5% of cal gas value	1.31%	0.5%	0.25%	0.5%
high	≤ 5% of cal gas value	1.61%	2.89%	4.38%	4.88%
• Zero drift (2 hour)	2% of span	0%	0%	0%	0%
• Zero drift (24 hour)	2% of span	0%	0%	0%	0%
• Calibration drift (2 hour)	2% of span	0.099%	0.155%	0.30%	0.47%
• Calibration drift (24 hr)	2.5% of span	0.11%	0.42%	0.36%	0.64%
• Response time	15 minute maximum	55 sec	60 sec	53 sec	60 sec
• Operational period	168 hour minimum	720 hr	720 hr	720 hr	720 hr

TABLE E-2

SUMMARY OF DAILY AVERAGE EMISSIONS AND OPERATING DATA

HUNTER UNIT 2, TEST 1

24-HOUR DATA DRY STACK GAS CONCENTRATION									
DATE 1983	LOAD MW_{th}	LOAD MW_e	O_2 vol% meas	CO_2 vol% meas	CO ppmv meas	NO ppmv 3%O_2	CO ng/J	NO* ng/J	NO* lb/MBtu
10/23	622.0	308.0	4.1	16.6	126	334	41	193	0.45
10/24	622.1	307.9	3.6	16.8	141	324	47	187	0.44
10/27	476.6	233.6	5.1	13.8	7	327	3	189	0.44
10/28	526.1	261.5	4.9	14.2	7	331	3	191	0.45
10/30	443.9	205.2	6.1	14.2	10	355	4	205	0.48
10/31	444.5	205.3	5.9	14.3	7	398	3	230	0.54
11/1	464.9	215.6	7.2	13.5	8	400	3	231	0.54
11/2	440.0	215.0	7.5	12.3	29	415	12	239	0.56
11/3	507.1	300.9	6.6	13.6	59	343	25	198	0.46
11/7	463.7	228.5	7.1	12.9	16	389	7	224	0.52
11/12	603.8	293.0	4.5	15.6	83	279	29	161	0.38
11/13	734.4	348.1	0.6	13.6	34	276	13	159	0.37
11/14	710.6	348.5	3.7	17.3	36	260	13	150	0.35
11/15	721.4	350.2	3.5	17.7	133	253	44	146	0.34
11/16	684.6	329.1	3.6	18.1	72	265	26	153	0.36
11/17	734.0	355.4	4.4	17.1	150	312	51	180	0.42
11/18	736.3	353.9	4.8	16.5	28	297	11	171	0.40
11/20	655.8	315.9	6.3	14.3	25	312	11	180	0.42
11/21	664.0	361.7	5.9	16.0	45	300	18	173	0.40
11/22	656.4	320.5	5.9	14.7	83	289	33	167	0.39
11/23	566.7	271.7	6.6	13.9	48	294	20	169	0.39
11/24	567.5	265.4	7.5	12.5	18	362	8	209	0.49
11/25	437.5	200.0	6.7	13.4	20	314	9	181	0.42
11/26	595.1	274.4	7.3	12.8	83	343	34	198	0.46
11/27	643.8	311.0	6.3	14.0	115	270	45	156	0.36
11/28	600.4	286.5	6.1	14.0	97	330	38	190	0.44
11/29	723.8	347.7	7.1	12.8	44	302	19	174	0.41
11/30	708.0	341.5	7.6	12.2	101	333	43	192	0.45
12/1	634.5	297.7	7.0	13.4	50	356	22	205	0.48
12/2	662.5	316.8	6.1	14.3	73	289	30	166	0.39

* The NO mass emission rates are in terms of NO_2.

TABLE E-3

SUMMARY OF DAILY AVERAGE EMISSIONS AND OPERATING DATA

HUNTER UNIT 2, TEST 2

24-HOUR DATA DRY STACK GAS CONCENTRATION									
DATE 1983	LOAD MW_{th}	LOAD MW_e	O_2 vol% meas	CO_2 vol% meas	CO ppmv meas	NO ppmv $3\%O_2$	CO ng/J	NO* ng/J	NO* lb/MBtu
4/8	599.2	288.9	3.7	16.9	40	325	14	188	0.44
4/9	572.4	274.8	4.1	16.5	28	338	10	196	0.46
4/10	585.6	280.9	4.0	15.9	31	331	11	192	0.45
4/11	749.5	333.7	3.4	16.8	27	312	10	180	0.42
4/12	605.7	292.0	3.7	16.3	26	313	9	181	0.42
4/13	628.2	302.7	3.4	16.8	24	303	9	175	0.41
4/14	650.5	314.5	3.5	16.5	30	303	11	175	0.41
4/15	619.3	300.8	3.5	16.4	27	294	10	170	0.40
4/16	636.7	307.8	2.9	17.1	31	287	11	166	0.39
4/17	585.7	281.5	4.0	16.3	33	301	11	174	0.41
4/18	572.3	274.2	4.0	15.9	25	329	9	190	0.44
4/19	591.1	283.4	3.8	16.1	57	288	20	166	0.39
4/20	619.7	307.1	3.2	16.8	32	290	11	168	0.39
4/22	592.2	285.3	3.7	16.2	63	303	22	175	0.41
4/23	544.3	259.5	4.1	15.4	31	299	11	173	0.40
4/24	607.3	289.7	3.6	16.0	27	291	10	168	0.39
4/25	570.7	272.9	3.9	15.8	30	283	11	163	0.38
4/26	608.4	297.6	3.7	15.9	29	299	11	173	0.40
4/29	548.0	264.4	5.4	14.5	23	329	10	190	0.44
4/30	597.3	286.7	5.2	14.8	25	311	10	180	0.42
5/1	538.7	256.1	3.9	16.0	25	292	9	169	0.39
5/2	589.3	281.4	3.4	16.5	25	303	9	175	0.41
5/3	611.6	293.0	3.3	16.6	28	299	10	173	0.40
5/4	582.7	290.7	3.2	16.7	33	298	12	172	0.40
5/5	636.4	304.5	3.2	16.7	29	297	10	172	0.40
5/10	590.3	285.8	3.9	16.3	25	293	9	170	0.40
5/11	594.8	285.4	4.4	17.1	25	312	9	181	0.42
5/12	602.0	289.5	4.1	17.0	25	308	9	178	0.41
5/13	583.6	280.0	3.9	16.6	21	304	8	176	0.41
5/14	597.4	292.5	4.0	15.9	22	312	8	180	0.42

* The NO mass emission rates are in terms of NO_2.

TABLE E-4
SUMMARY OF DAILY AVERAGE EMISSIONS AND OPERATING DATA
HUNTER UNIT 2, TEST 3

24-HOUR DATA DRY STACK GAS CONCENTRATION									
DATE 1983	LOAD MW_{th}	LOAD MW_e	O_2 vol% meas	CO_2 vol% meas	CO ppmv meas	NO ppmv 3%O_2	CO ng/J	NO* ng/J	NO* lb/MBtu
6/19	624.5	298.0	2.9	16.7	26	284	9	162	0.38
6/20	617.4	291.7	2.5	17.3	26	275	9	157	0.37
6/21	567.9	267.0	3.7	16.0	20	296	7	169	0.39
6/22	567.8	267.7	4.1	15.7	18	304	7	174	0.41
6/23	590.7	279.1	3.4	16.3	20	290	7	166	0.39
6/24	632.8	298.1	2.8	17.1	20	289	7	165	0.38
6/25	628.6	297.5	3.3	16.5	23	301	8	172	0.40
6/26	597.1	282.7	3.7	15.9	21	283	7	162	0.38
6/27	564.8	266.0	3.5	16.1	17	293	6	167	0.39
6/29	561.3	264.6	3.6	15.9	21	269	8	154	0.36
6/30	565.3	266.5	3.0	16.8	26	267	9	153	0.36
7/1	544.5	257.9	3.7	15.9	24	294	8	168	0.39
7/2	634.3	299.9	3.2	16.6	22	274	8	156	0.36
7/3	599.9	279.4	3.6	16.2	22	293	8	168	0.39
7/4	608.3	290.3	3.1	0.0**	27	295	9	169	0.39
7/5	595.6	282.9	2.5	0.0	23	268	8	153	0.36
7/6	580.9	274.7	3.2	0.0	21	288	7	165	0.38
7/7	578.3	267.2	3.0	0.0	21	272	7	156	0.36
7/8	580.9	274.7	3.1	0.0	23	286	8	163	0.38
7/9	600.4	270.7	2.4	0.0	48	257	16	147	0.34
7/10	578.3	267.2	4.3	0.0	23	320	8	183	0.43
7/11	584.9	258.9	2.8	0.0	21	284	7	162	0.38
7/12	556.3	261.2	3.1	0.0	22	284	8	162	0.38
7/16	565.7	265.2	3.9	16.0	28	296	10	169	0.39
7/17	575.1	270.7	3.6	16.4	33	281	11	161	0.38
7/18	605.4	284.4	2.6	17.4	43	274	14	156	0.36
7/19	582.8	273.3	3.4	16.4	25	289	9	165	0.38
7/20	608.9	287.2	2.6	17.5	30	268	10	153	0.36
7/21	545.6	252.5	3.5	16.2	30	282	11	161	0.38
7/22	567.8	265.8	3.4	16.4	25	278	9	159	0.37

* NO on a mass basis is in terms of NO_2.

**CO_2 analyzer was out-of-service from July 4 through July 12, 1983.

TABLE E-5

SUMMARY OF DAILY AVERAGE EMISSIONS AND OPERATING DATA

HUNTER UNIT 2, TEST 4

24-HOUR DATA DRY STACK GAS CONCENTRATION									
DATE 1983	LOAD MW_{th}	LOAD MW_e	O_2 vol% meas	CO_2 vol% meas	CO ppmv meas	NO ppmv 3%O_2	CO ng/J	NO* ng/J	NO* lb/MBtu
7/25	659.0	312.2	2.9	17.1	36	281	13	165	0.38
7/26	619.0	291.4	2.9	17.1	34	280	12	165	0.38
7/27	662.8	315.4	4.1	15.7	33	276	12	162	0.38
7/29	614.2	284.0	2.8	17.1	46	330	16	194	0.45
7/30	605.4	293.6	3.7	16.2	38	277	14	163	0.38
7/31	650.6	308.1	2.9	17.0	31	272	11	160	0.37
8/1	565.8	262.5	3.8	15.9	23	263	9	155	0.36
8/2	533.4	245.8	4.6	14.9	26	307	10	180	0.42
8/3	547.7	256.7	5.1	14.3	20	358	8	210	0.49
8/4	536.6	240.7	4.2	15.3	22	323	9	190	0.44
8/5	663.8	347.9	3.1	16.7	28	281	10	165	0.38
8/6	634.2	300.3	3.1	16.7	26	299	9	176	0.41
8/7	547.7	256.7	4.3	15.3	22	305	8	180	0.42
8/8	552.3	259.5	4.0	15.6	20	331	8	195	0.45
8/9	479.9	230.3	5.1	14.3	19	356	8	209	0.49
8/10	616.3	268.1	3.8	15.9	22	309	8	182	0.42
8/11	563.7	265.5	3.6	16.2	23	315	9	185	0.43
8/12	575.0	271.2	4.0	15.6	23	314	9	185	0.43
8/13	504.3	232.2	5.1	14.2	19	337	8	198	0.46
8/15	582.7	276.4	4.0	15.6	26	316	10	186	0.43
8/16	544.9	256.2	3.8	15.9	23	321	8	189	0.44
8/17	548.9	257.6	3.9	15.7	21	306	8	180	0.42
8/18	545.2	256.2	3.8	15.9	24	306	9	180	0.42
8/19	548.4	257.7	3.6	16.1	23	288	9	170	0.4
8/20	558.2	261.3	4.0	15.6	25	254	10	150	0.35
8/21	568.9	267.2	4.1	15.5	22	301	8	177	0.41
8/22	569.7	264.5	4.0	15.7	21	331	8	194	0.45
8/25	602.5	286.7	3.5	16.2	26	266	10	157	0.37
8/26	551.5	256.5	4.4	15.2	26	305	10	179	0.42
8/27	578.6	272.5	3.9	16.0	24	326	9	192	0.45

* The NO mass emission rates are in terms of NO_2.

TABLE E-6 (pg 1 of 2)

STATISTICAL PARAMETERS FOR HUNTER UNIT NO. 2
30 DAY FIELD TESTS

FIRST 30-DAY TEST

	Load (MW_{th})	Load (MW_e)	O_2 (%)	CO_2 (%)	CO (ng/J)	NO* (ng/J)	NO* (lb/MBtu)
Minimum	437.5	200.0	3.5	12.2	3	146	0.19
Maximum	736.3	361.7	7.6	18.1	51	239	0.56
Mean	600.4	291.6	5.9	14.5	22	179	0.42
Variance = $(SD)^2$	10733.0	2695.7	1.695	2.90	235.52	614.05	0.004
Standard Deviation (SD)	103.6	51.92	1.302	1.703	15.347	24.78	0.06
Count	29	30	30	30	30	30	30
Percent Deviation	17.3	18.0	22.1	11.7	69.8	13.3	14.0

SECOND 30-DAY TEST

	Boiler Load (MW_{th})	Elec. Load (MW_e)	O_2 (%)	CO_2 (%)	CO* (ng/J)	NO* (ng/J)	NO* (lb/MBtu)
Minimum	538.7	256.1	2.9	14.5	8	163	0.38
Maximum	749.5	333.7	5.4	17.1	22	196	0.46
Mean	600.5	288.8	3.8	16.3	11	177	0.41
Variance = $(SD)^2$	1536	258	0.28	0.36	9.3	64.6	0.0004
Standard Deviation (SD)	39.2	16.1	0.53	0.60	3.0	8.0	0.02
Count	30	30	30	30	30	30	30
Percent Deviation	6.5	5.6	14.0	3.7	28.3	4.6	4.6

*NO mass emission rates are in terms of NO_2. (NO represents ~95% of the total NO_x emissions.)

TABLE E-6 (pg 2 of 2)

STATISTICAL PARAMETERS FOR HUNTER UNIT NO. 2
30 DAY FIELD TESTS

THIRD 30-DAY TEST

	Boiler Load (MW_{th})	Elec. Load (MW_e)	O_2 (%)	CO_2 (%)	CO (ng/J)	NO* (ng/J)	NO* (lb/MBtu)
Minimum	544.5	231.8	2.4	15.7	6	147	0.34
Maximum	634.3	299.9	4.3	17.5	16	183	0.43
Mean	587.3	273.12	3.25	16.4	7	163	0.38
Variance = $(SD)^2$	622.0	273	0.24	0.28	4.5	56.5	0.0004
Standard deviation (SD)	24.9	16.5	0.48	0.52	2.1	7.5	0.02
Count	30	30	30	21	30	30	30
Percent Deviation	4.2	6.0	14.9	3.2	30.3	4.6	4.6

FOURTH 30-DAY TEST

	Boiler Load (MW_{th})	Elec. Load (MW_e)	O_2 (%)	CO_2 (%)	CO (ng/J)	NO* (ng/J)	NO* (lb/MBtu)
Minimum	479.9	230.3	2.8	14.2	8	150	0.35
Maximum	663.8	347.9	5.1	17.1	16	210	0.49
Mean	577.4	271.4	3.9	15.8	10	179	0.42
Variance = $(SD)^2$	2142	679	0.39	0.61	4.0	239.3	0.0013
Standard Deviation (SD)	46.3	26.1	0.62	0.78	2.0	15.5	0.04
Count	30	30	30	30	30	30	30
Percent Deviation	8.0	9.6	16.2	5.0	19.9	8.6	8.6

*NO on a mass basis is in terms of NO_2. (NO represents ~95% of the total NO_x emissions.)

mean value of the daily average stack oxygen content was 3.8 percent with a standard deviation (from day-to-day) of 0.53 percent O_2, or 14 percent of the mean value. Similarly, the mean daily 24 hour average NO value (as equivalent NO_2) was 177 ng/J (0.41 lb/MBtu) with a standard day-to-day deviation of 8 ng/J or 4.6 percent of the mean value.

The 24-hour average data were plotted as a function of time from the start of testing. Figures E-1, E-2, E-3, and E-4 show the variation in the boiler's average daily load as a function of time for each of the four 30-day tests. (The daily averages used in this figure were obtained from the unit operators.)

Note that starting with Test No. 2, the daily averages are relatively steady, and are typically about 65% of capacity. This is typical of the recent operating history for this boiler.

Figures E-5 through E-16 show the gaseous emissions (NO_x, CO, and O_2) as a function of time for the four CEM test periods. All the gaseous emissions show variations in the daily averages due to swings in boiler load and operating conditions. However, emission rates and operating conditions were steadier during some tests (No. 4, for example) than others (No. 1 for example). The figures show that for Test No. 4 for example (Figures E-14 E-15, and E-16) the average daily oxygen concentration (Figure E-16 varied from a minimum of 2.8 percent to a maximum of 5.1 percent with a mean value of 3.9 percent. The percent deviation was 16.2 percent (compared to 22.1 percent for Test No. 1 and 14.9 percent for Test No. 3). CO emission rates are not as steady as the other gaseous emissions. For example, during Test No. 4, the CO emission rate ranged from 8 ng/J (22 ppm) to 16 ng/J (44 ppm) with a mean value of 10 ng/J (27 ppm) and a percent deviation of 19.9 percent. These and other normal distribution statistical parameters for Tests 1-4 are presented in Table E-6.

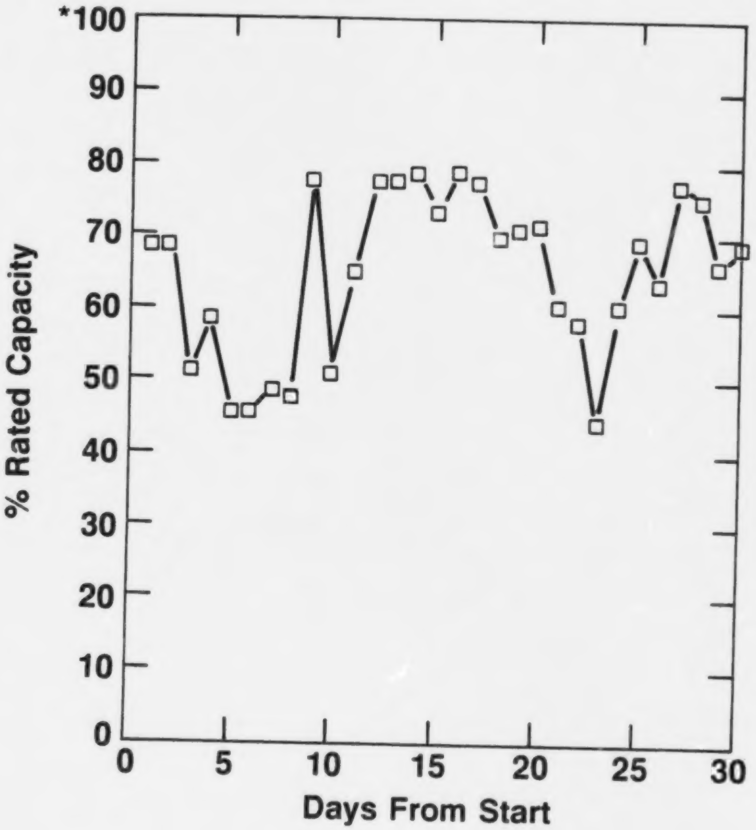

Figure E-1
Load History–Hunter No. 2
First 30-Day Test

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*100% Capacity = 425 MWe

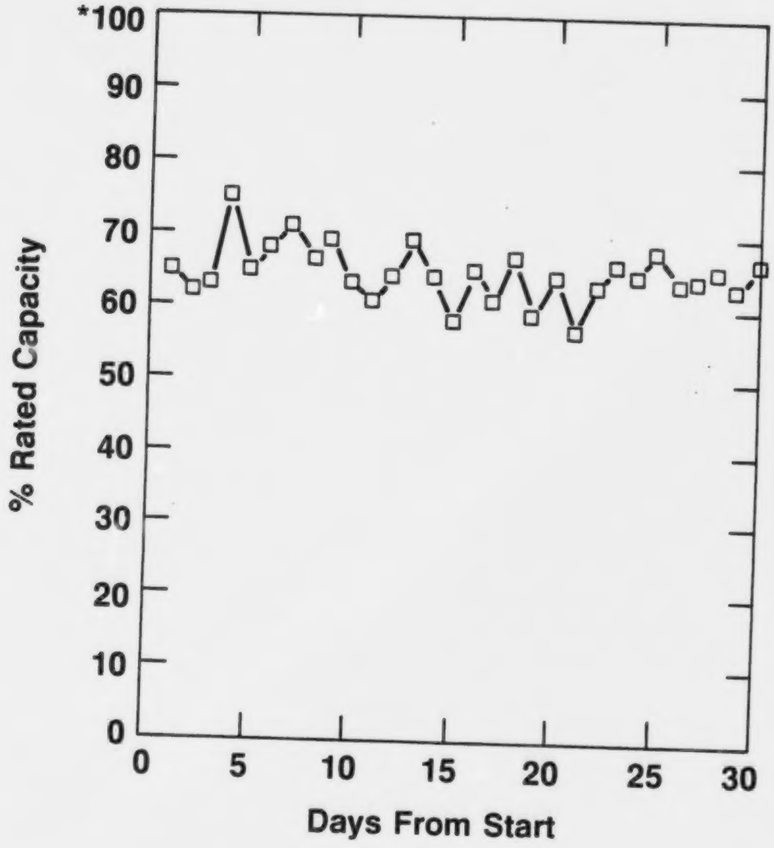

Figure E-2
Load History–Hunter No. 2
Second 30-Day Test

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*100% Capacity = 425 MWe

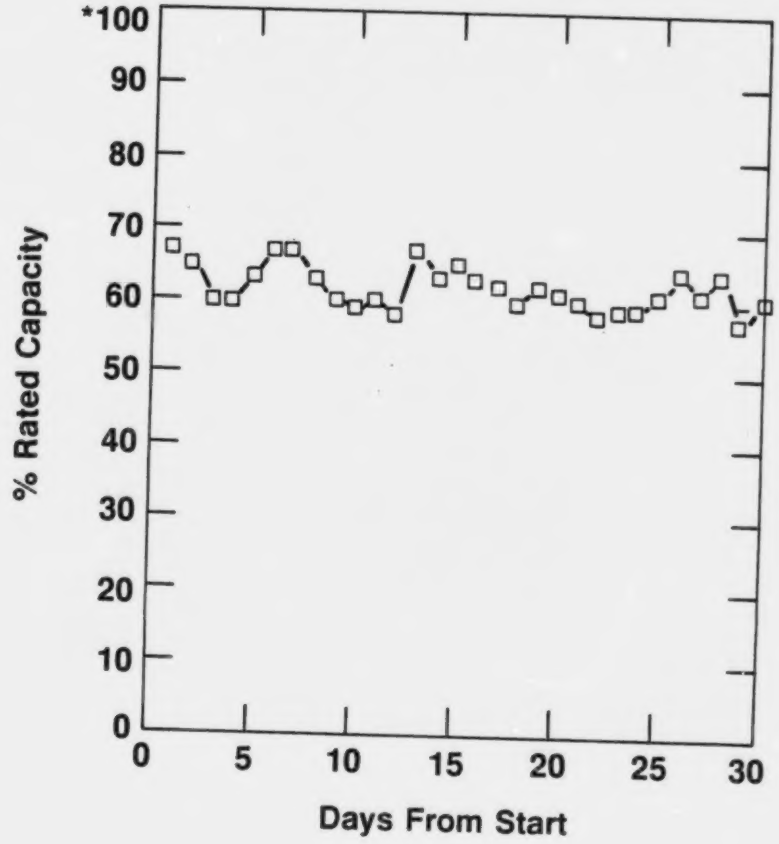

Figure E-3
Load History–Hunter No. 2
Third 30-Day Test

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*100% Capacity = 425 MWe

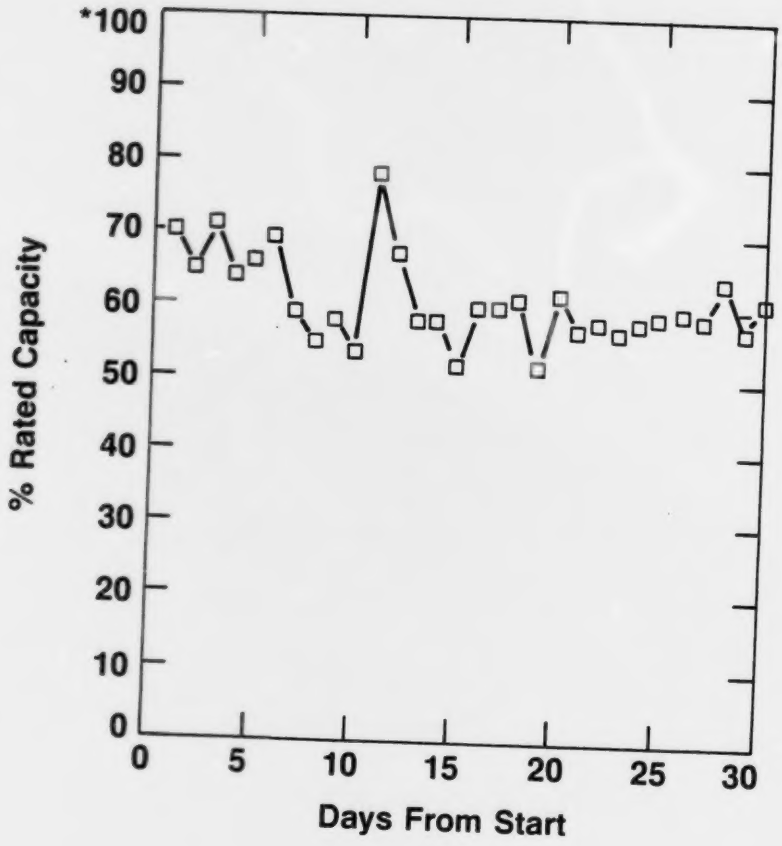

Figure E-4
Load History–Hunter No. 2
Fourth 30-Day Test

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*100% Capacity = 425 MWe

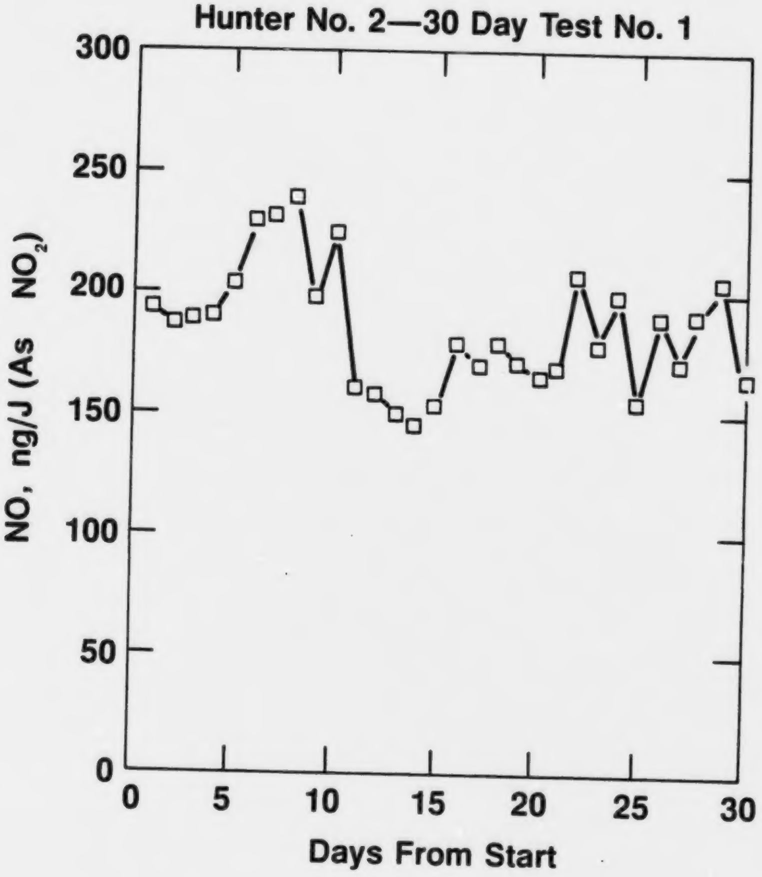


Figure E-5
Test No. 1: Daily Average NO Emissions as a Function of Time

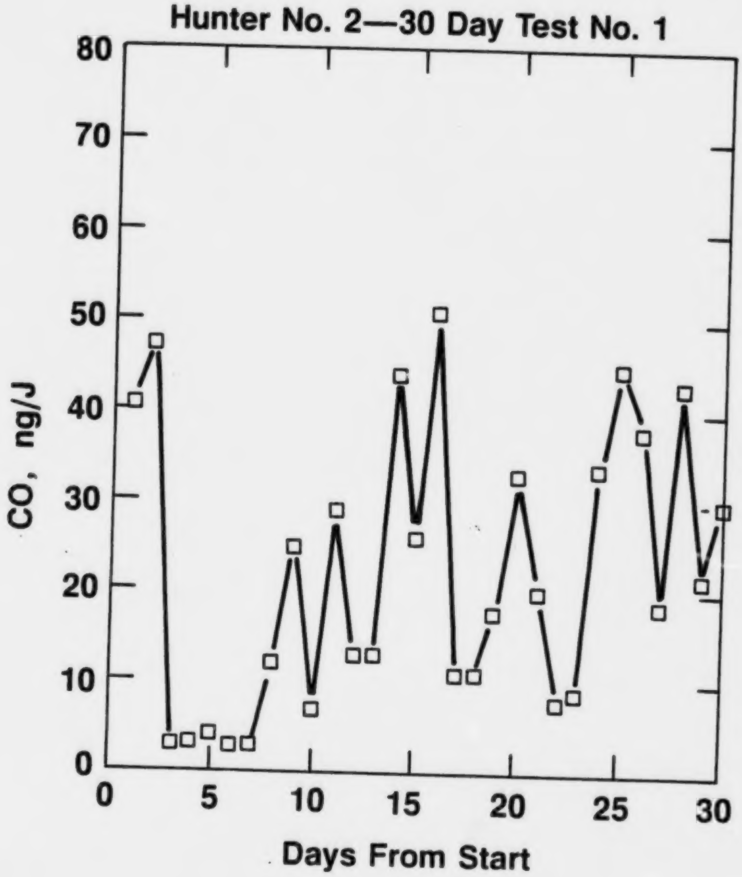


Figure E-6
Test No. 1: Daily Average CO Emissions as a Funciton of Time

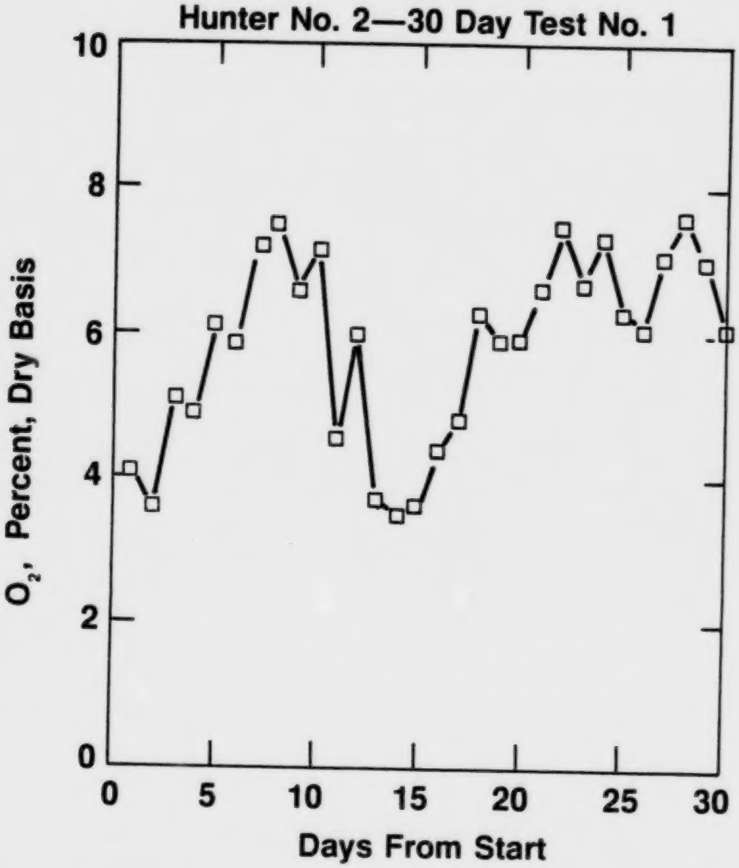


Figure E-7
Test No. 1: Daily Average O_2 Concentration as a Function of Time

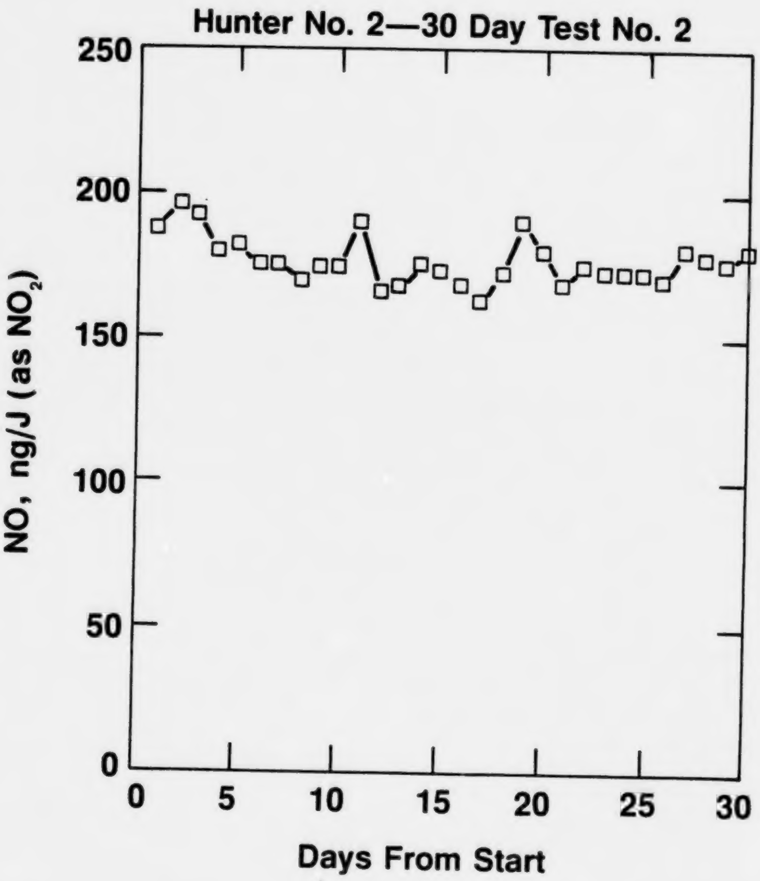


Figure E-8
Test No. 2: Daily Average NO Emission Rate as a Function of Time

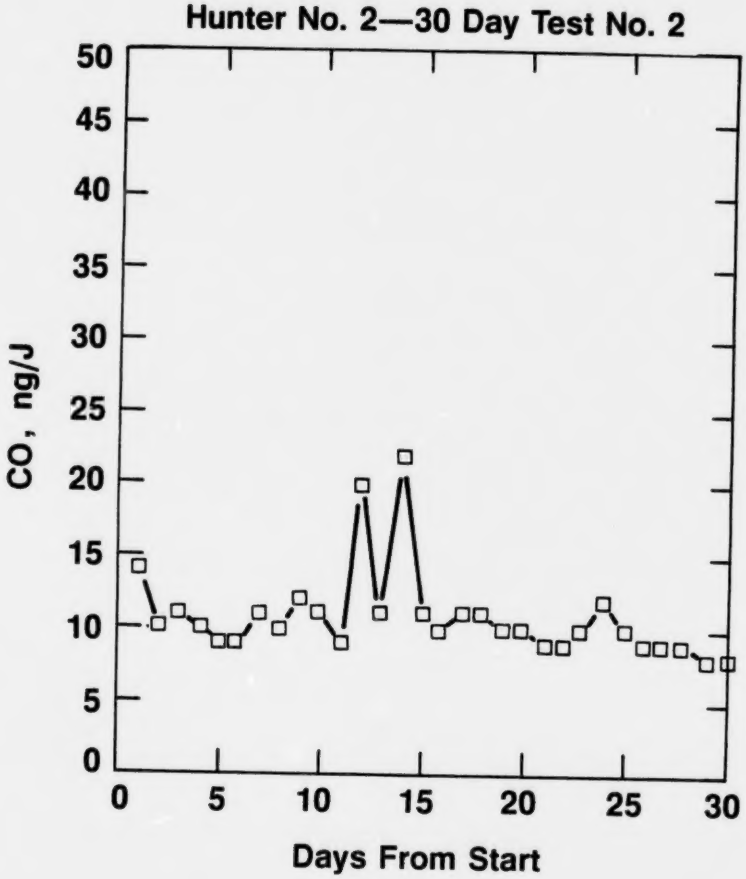


Figure E-9
Test No. 2: Daily Average CO Emission Rate
as a Function of Time

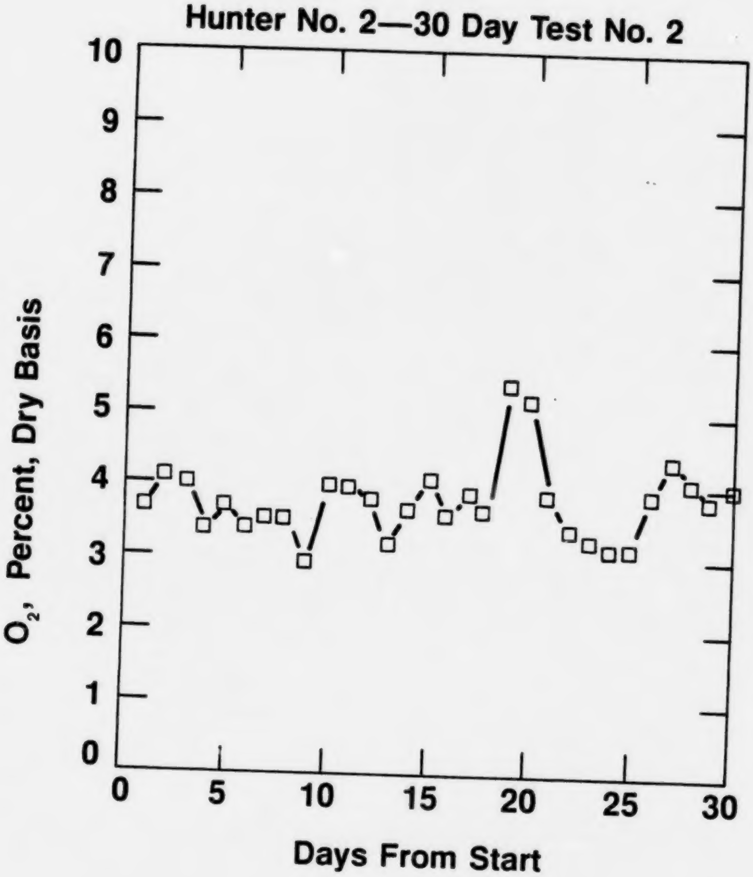


Figure E-10
Test No. 2: Daily Average Oxygen Concentration as a Function of Time

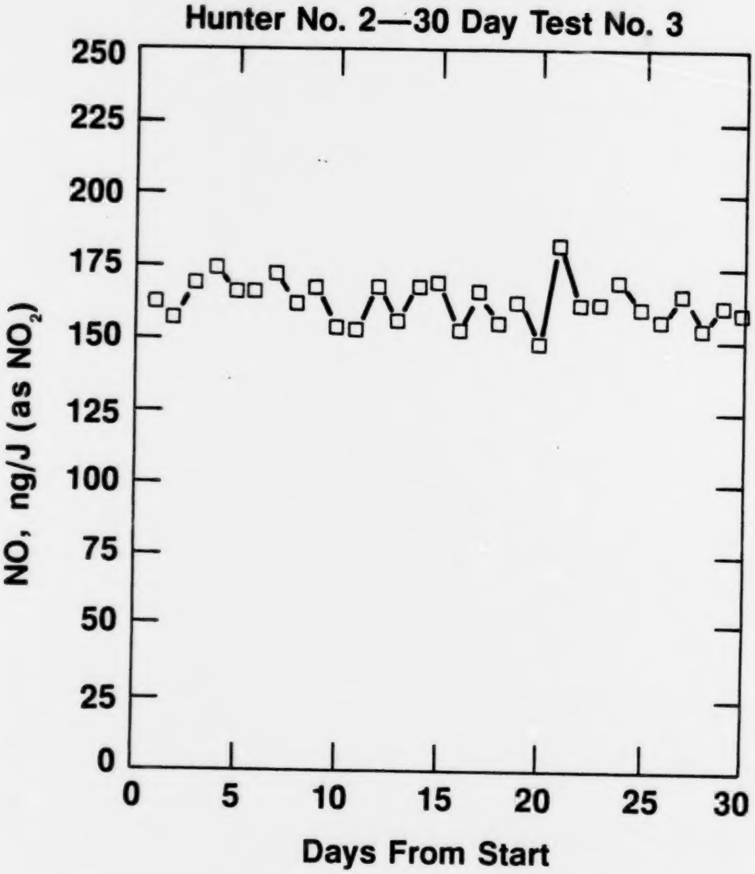


Figure E-11
Test No. 3: Daily Average NO Emission Rate
as a Function of Time

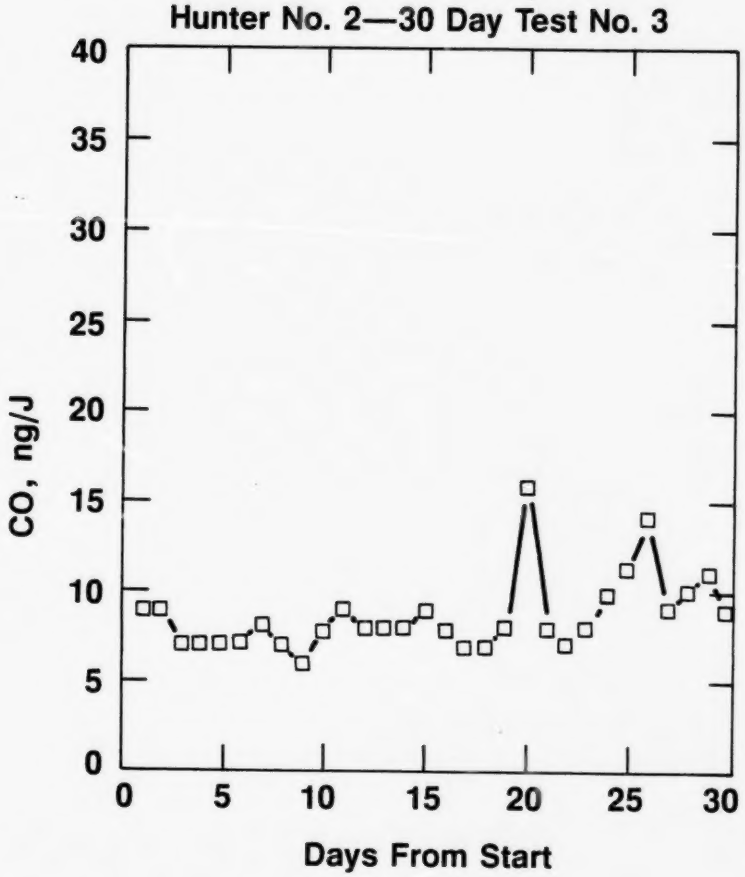


Figure E-12
Test No. 3: Daily Average CO Emission Rate
as a Function of Time

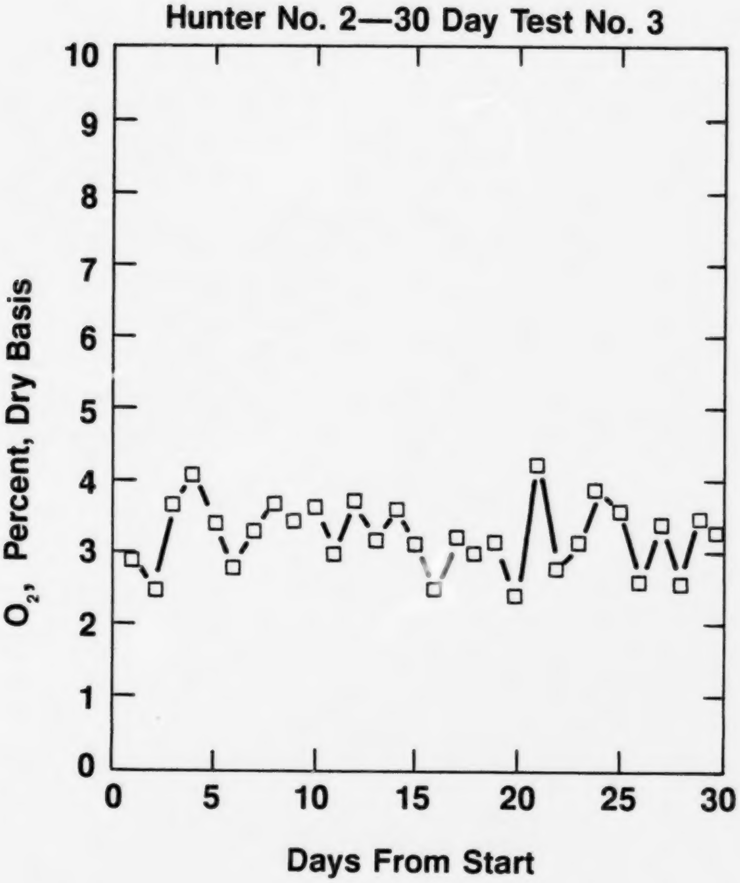


Figure E-13
Test No. 3: Daily Average O_2 Concentration as a Function of Time

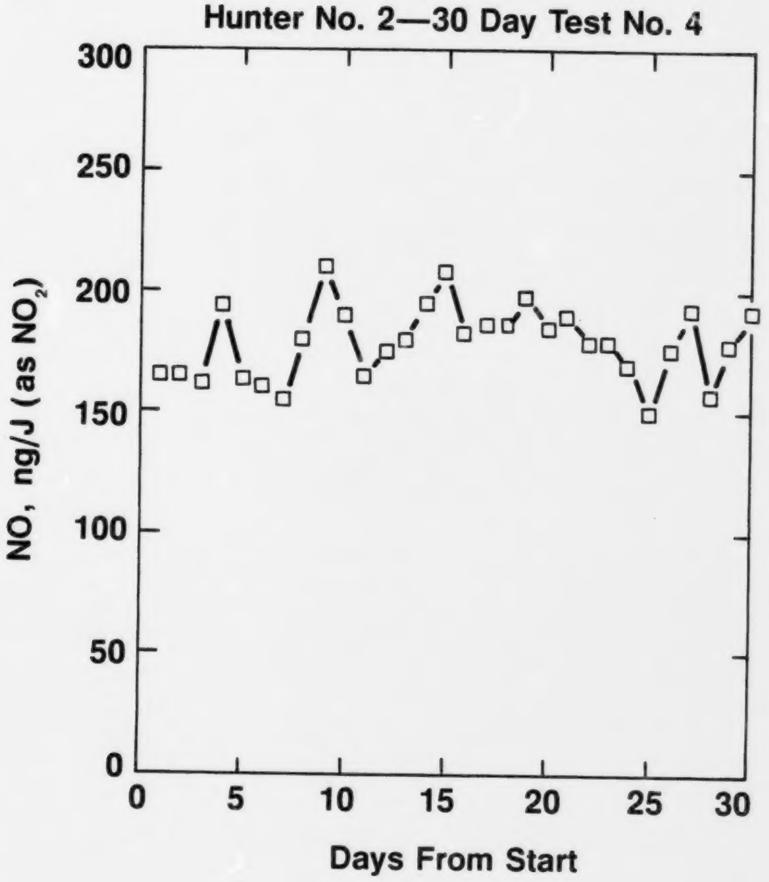


Figure E-14
Test No. 4: Daily Average NO Emission Rate as a Function of Time

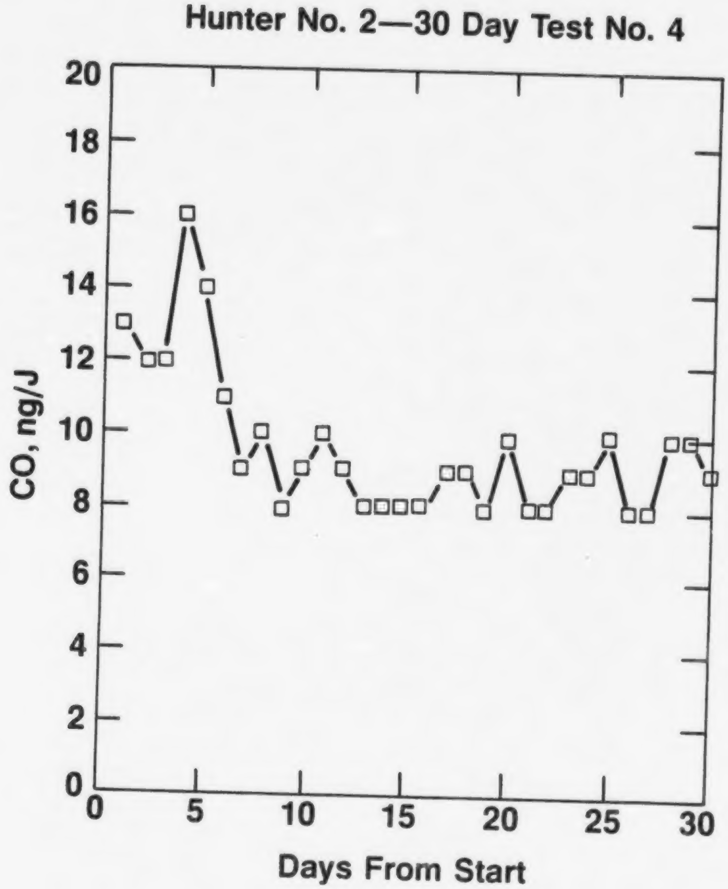


Figure E-15
Test No. 4: Daily Average CO Emission Rate
as a Function of Time

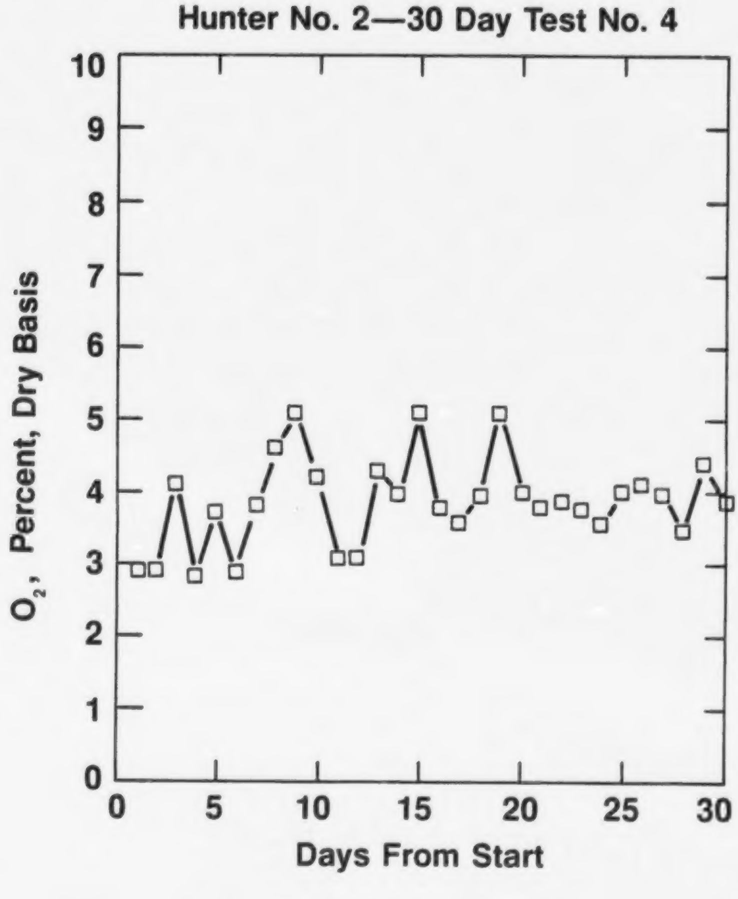


Figure E-16
Test No. 4: Daily Average O_2 Concentration as a Function of Time

The effects of boiler load on excess oxygen (an independently controlled parameter) and on NO emission rates are shown in Figures E-17 through E-24. These figures show a general trend toward slightly lower NO_x (ng/J) values as load is increased. (Of course increased load is accompanied by an intentional decrease in O_2 as shown in the figures.)

The NO emission rates vs. stack excess oxygen (daily averages, without consideration of load, etc.) are presented in Figures E-25 through E-28. Although there is considerable scatter in the data, the general trend is for an increase in NO emissions with increasing excess oxygen.

A summary of NO_x emissions versus load (MW_{th}) and excess oxygen levels is shown in Table E-7 which is simply a part of Table E-6. These results are best compared by reviewing the conditions under which the 30-day monitoring tests were run. Prior to the first test, the recommended excess oxygen and overfire air settings (as a function of load) were presented by C-E to UP&L (see Figure D-23 in Part D). Because the boiler was set up at conditions to minimize the large oxygen imbalances (discussed in Part D), single duct sampling was performed. The results from the first test indicated a higher excess oxygen concentration than expected. This suggested that either the control board operators were not strictly following the new recomendations (especially at lower loads) or that an oxygen imbalance still existed occasionally between the left and right flue ducts.

In response to this, during the second 30-day test, a greater emphasis was placed on following the recommended operating

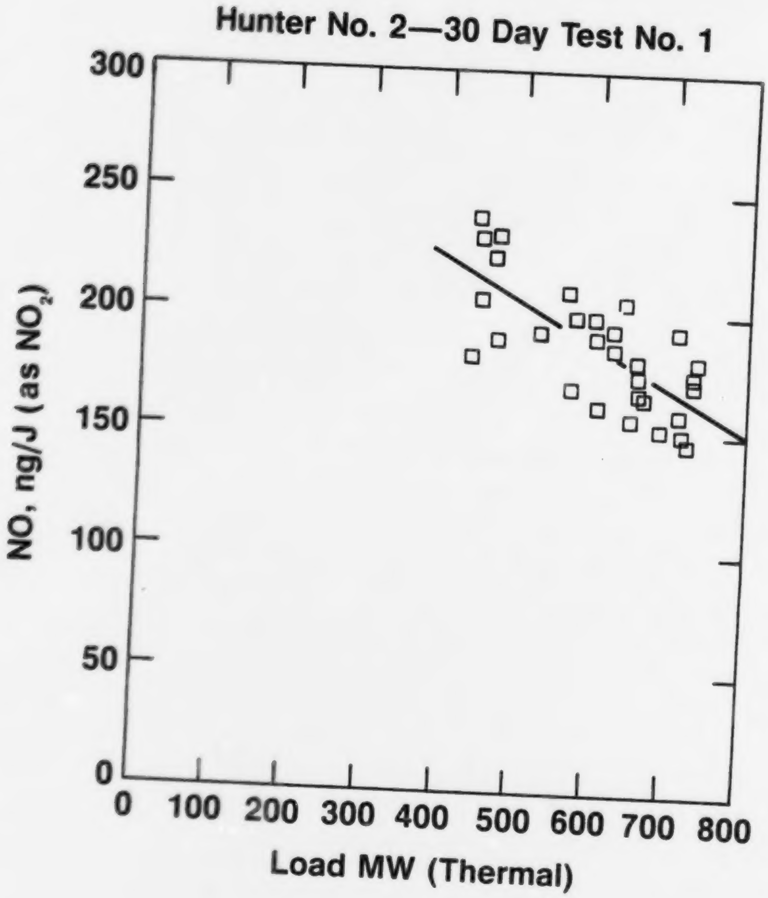


Figure E-17
Test No. 1: Effect of Boiler Steam Load on NO Emissions Rate

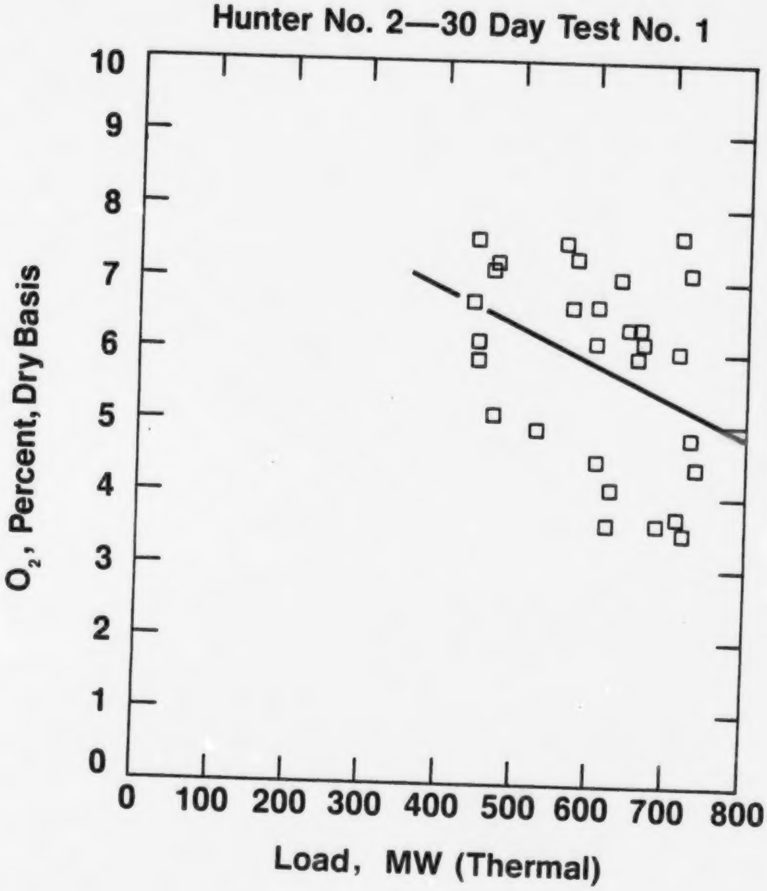


Figure E-18
Test No. 1: Stack Gas O_2 Concentration as a Function of Boiler Steam Load

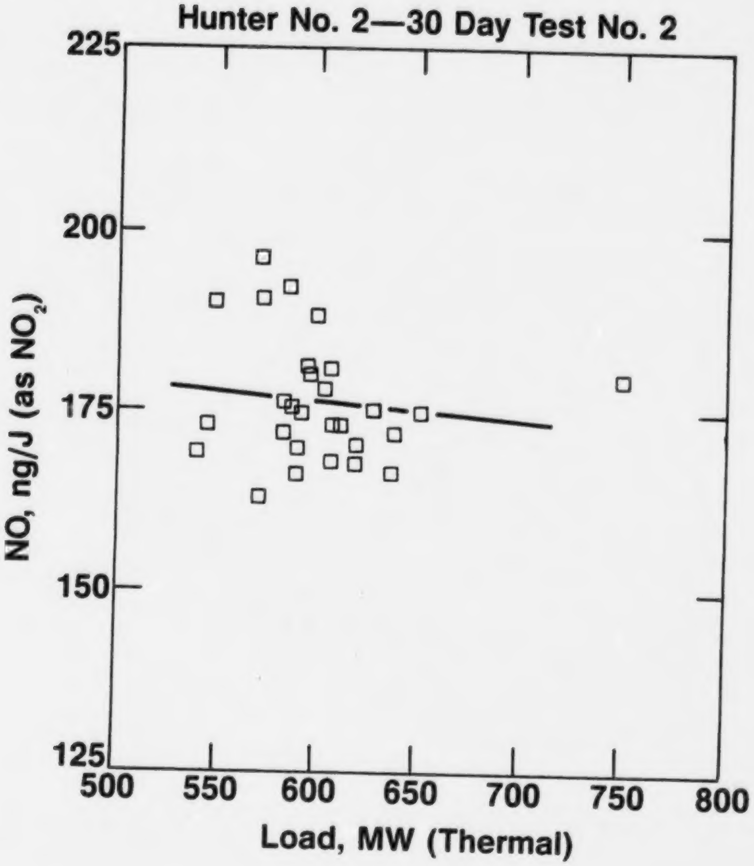


Figure E-19
Test No. 2: Effect of Boiler Load on NO Emission Rate

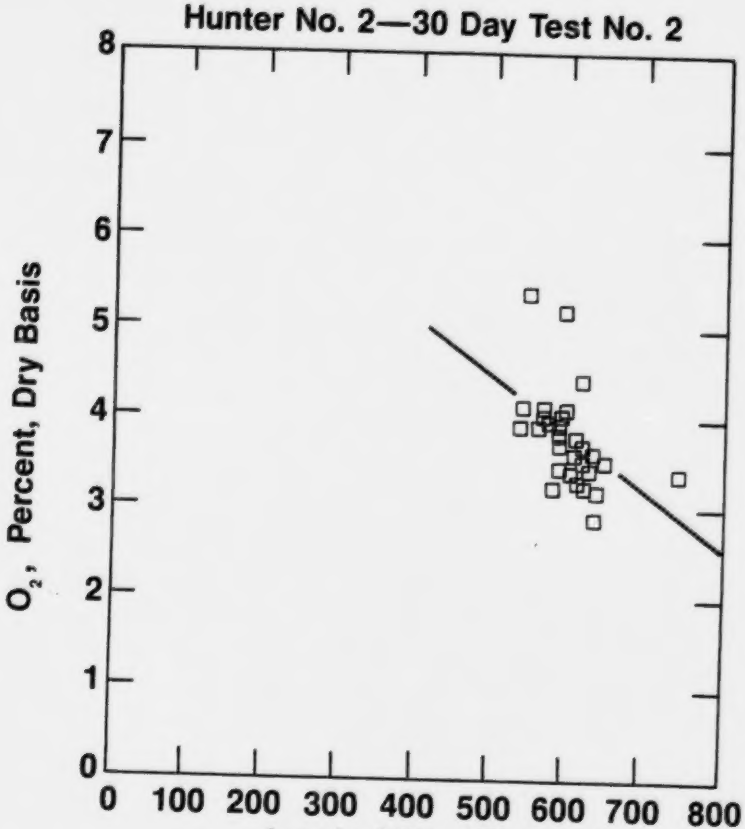


Figure E-20
Test No. 2: Stack Oxygen Content as a Function of Boiler Steam Flow

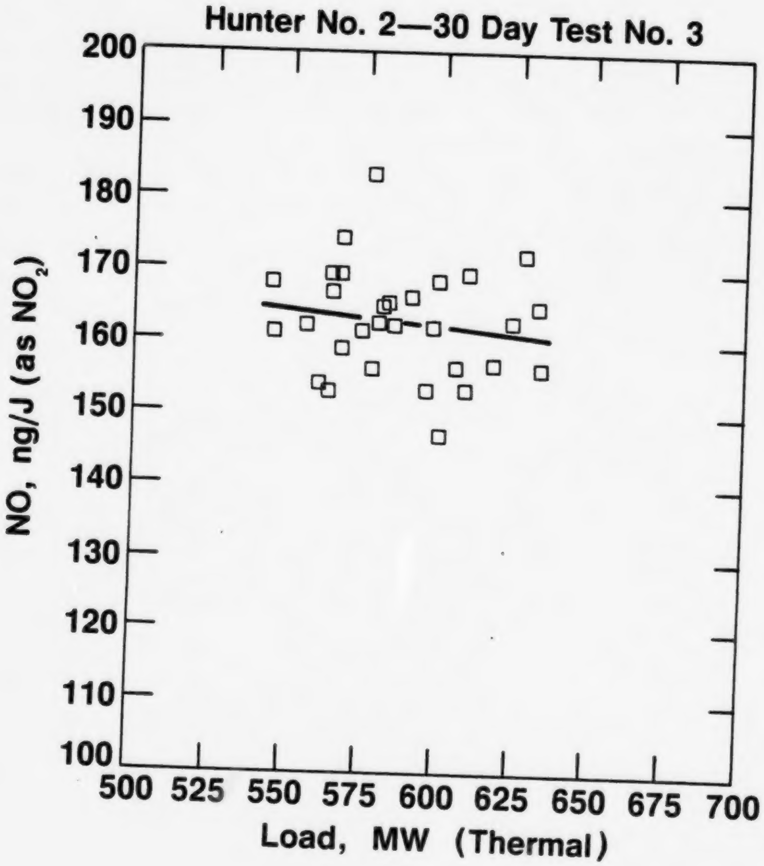


Figure E-21
Test No. 3: Effect of Boiler Load
on NO Emission Rate

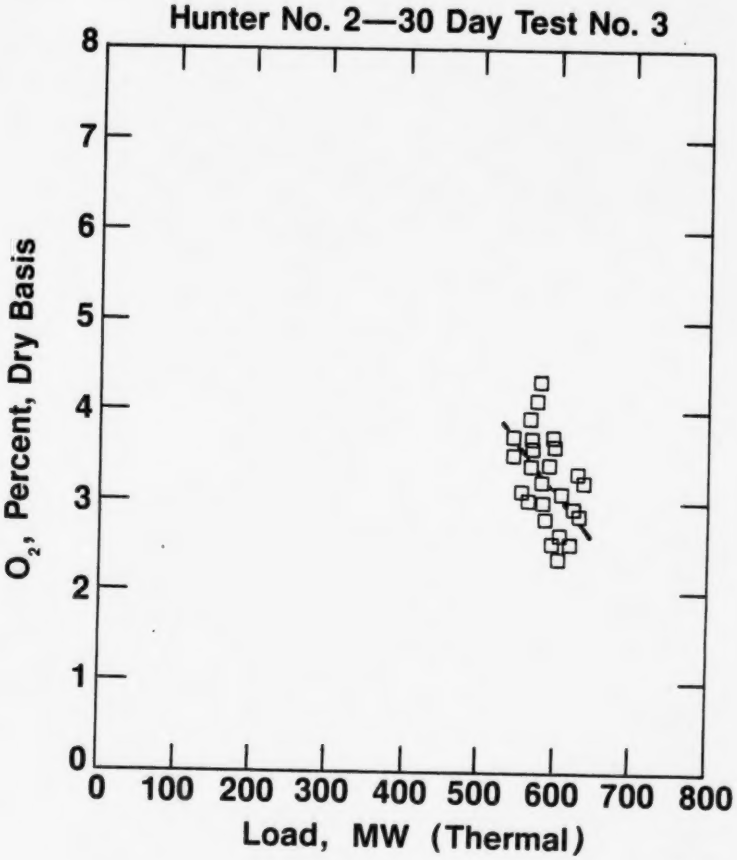


Figure E-22
Test No. 3: Effect of Boiler Steam Flow on Stack O_2 Concentration

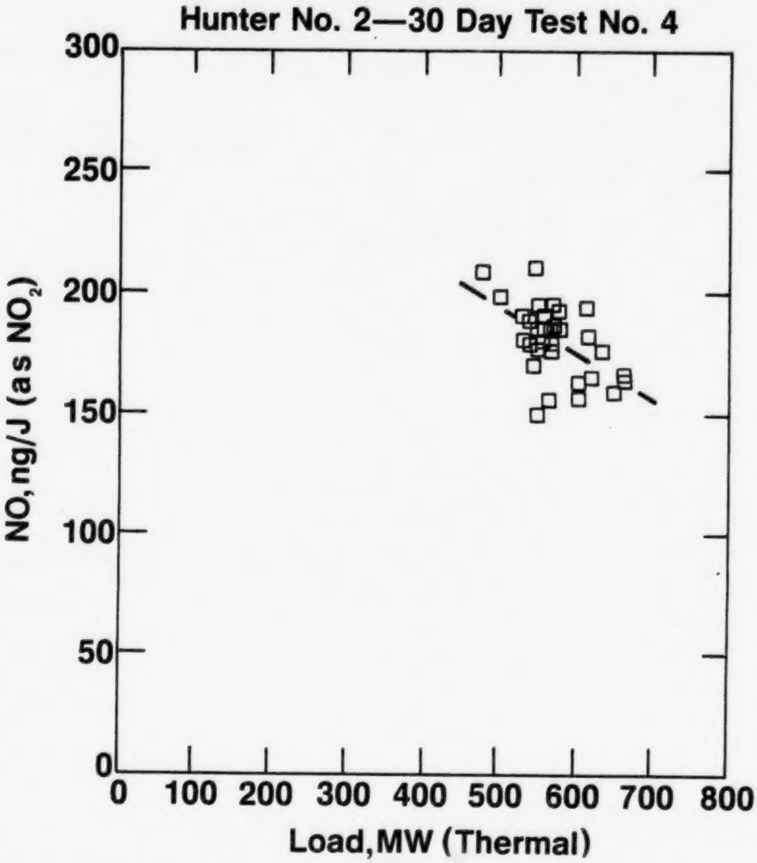


Figure E-23
Test No. 4: The Effect of Boiler Load
on NO Emission Rate

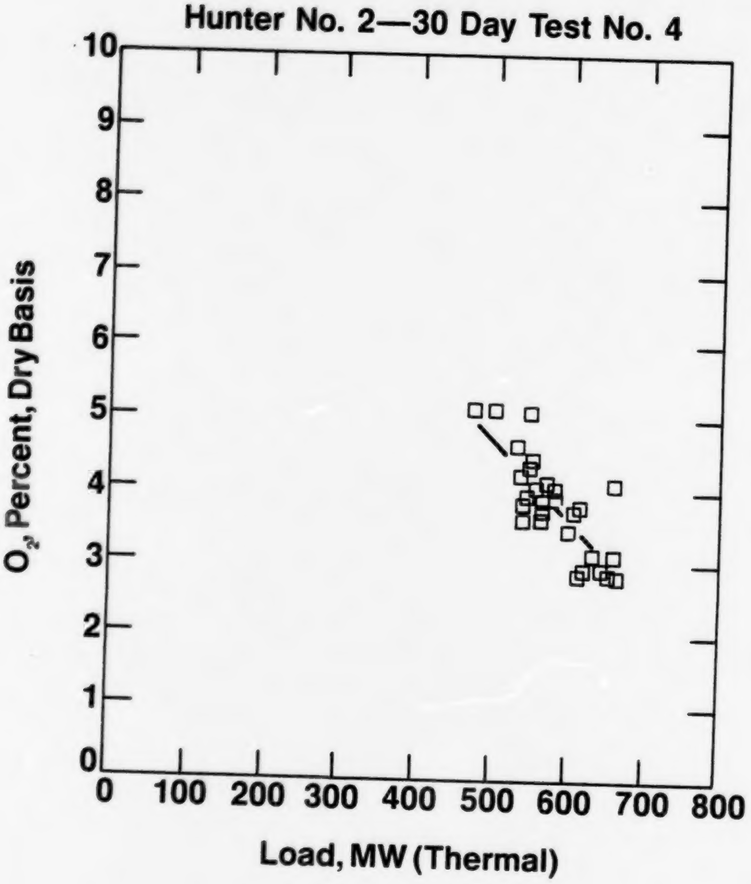


Figure E-24
Test No. 4: Effect of Boiler Load on Stack Oxygen Concentration

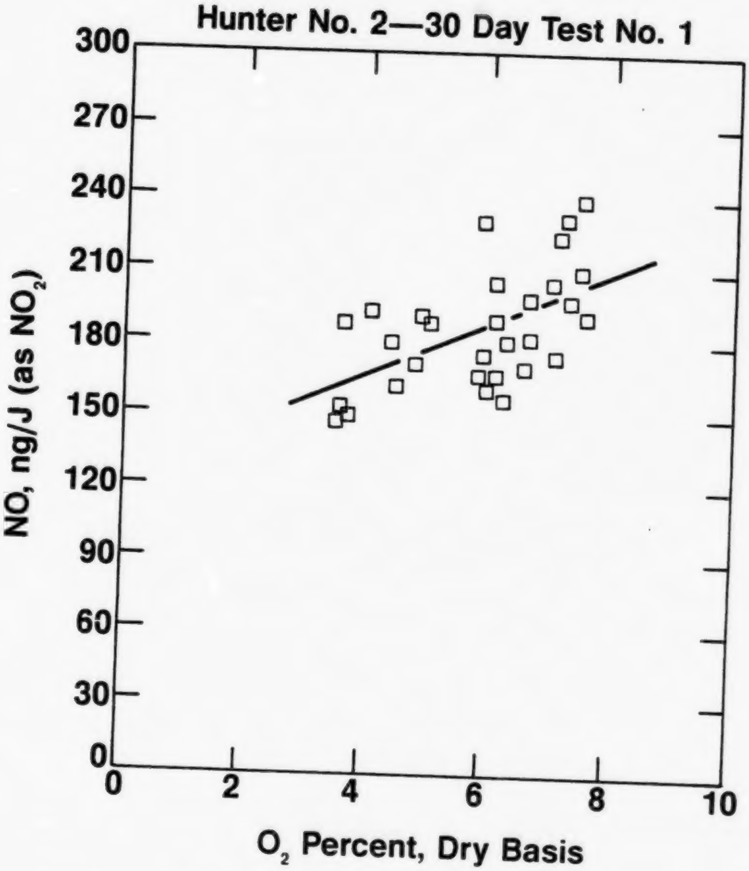


Figure E-25
Test No. 1: Effect of Boiler Stack O_2 Concentration on NO Emission Rate

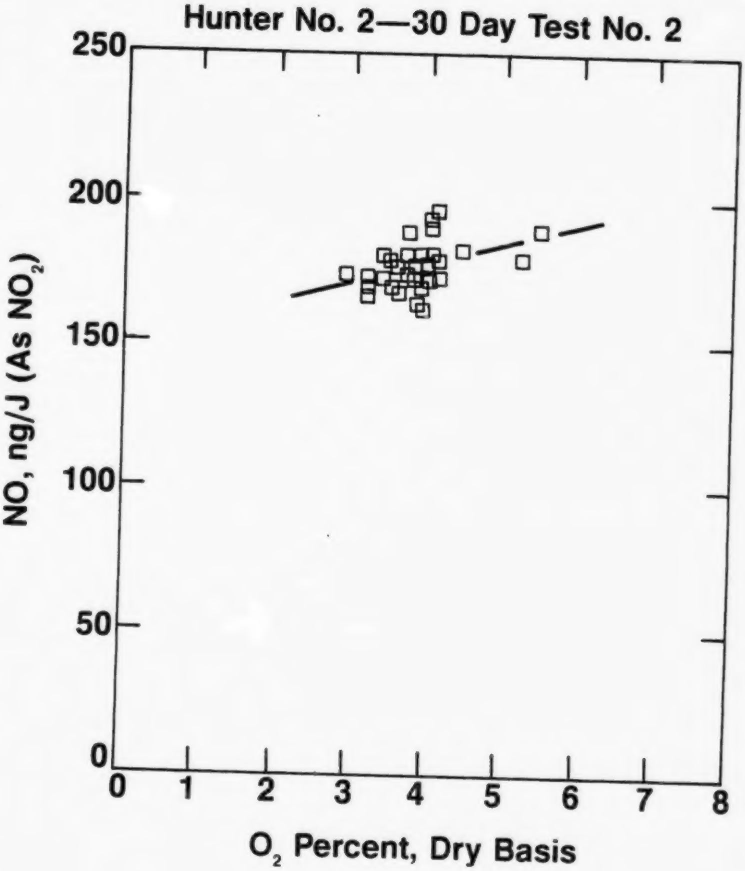


Figure E-26
Test No. 2: Effect of Stack Oxygen Content on NO Emission Rate

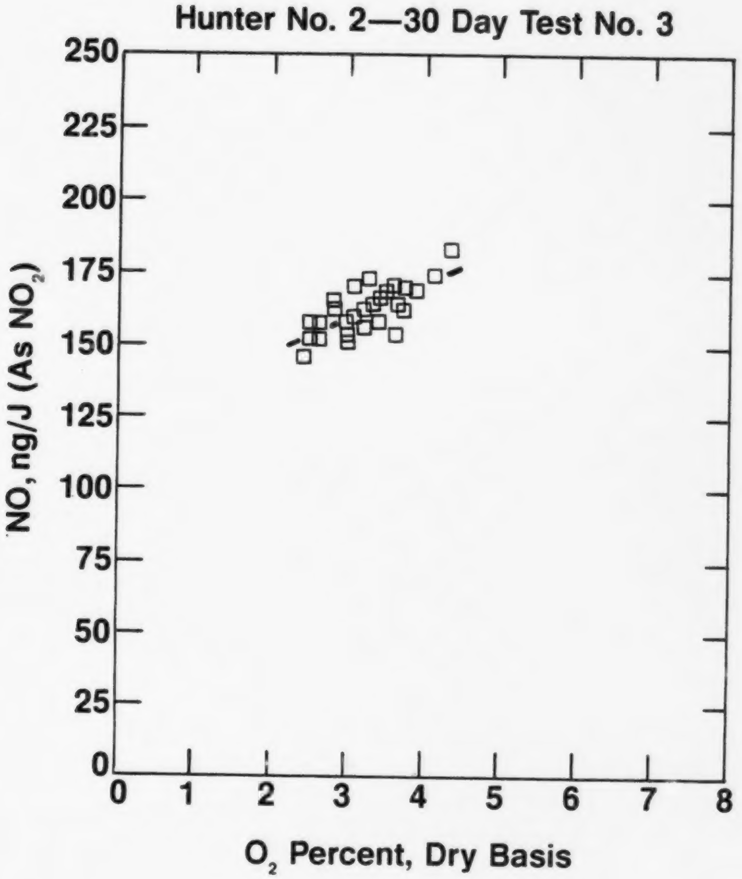


Figure E-27
Test No. 3: Effect of Stack Oxygen Concentration on NO Emission Rate

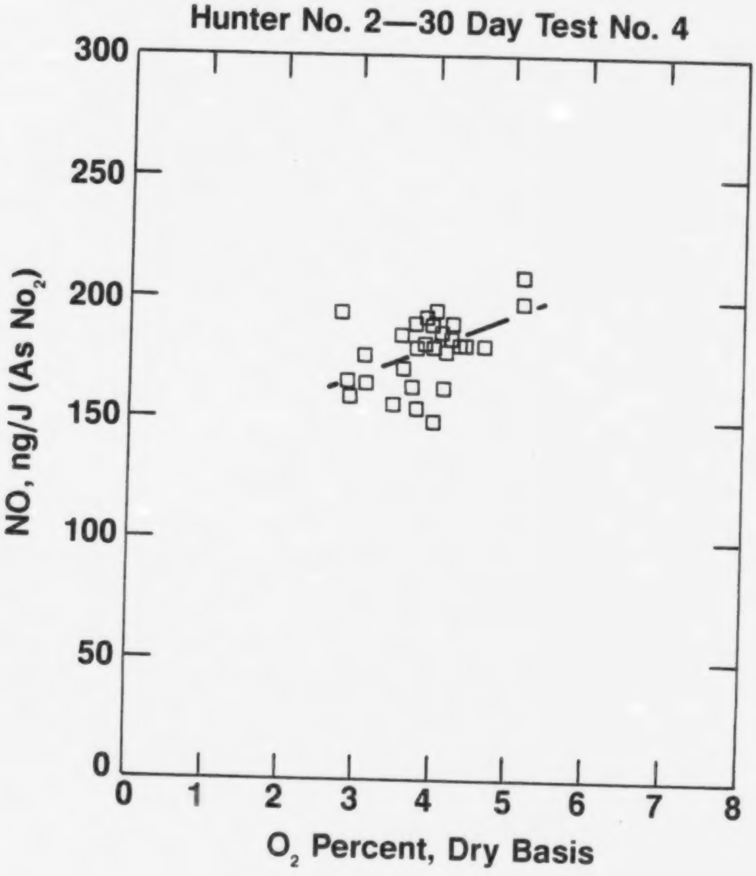


Figure E-28
Test No. 4: Effect of Boiler Stack O_2 Concentration on NO Emission Rate

TABLE E-7

SUMMARY OF 30-DAY CEM TEST RESULTS

Test No.	NO_x Levels		Load (mean) MW_{th}	% Excess Oxygen (dry)
	ng/J	lb/MBtu		
1	179	0.42	600	5.9
2	177	0.41	600	3.8
3	160	0.37	587	3.3
4	179	0.42	577	3.9

procedures while minimizing the occurrences of oxygen imbalances. As the results indicate, this helped to reduce the excess oxygen levels, but the NO_x levels decreased only slightly.

For the third 30-day monitoring tests, it was decided to try to achieve maximum long-term NO_x reductions by instituting an exceptional degree of boiler control. This was accomplished through the presence of onsite Exxon and C-E personnel for most of the third test. The results yielded lower excess oxygen levels while reducing the occurrences of oxygen imbalances. This subsequently lowered the NO_x levels.

For the fourth 30-day monitoring test, it was decided that the board operators' familiarity with the recommended C-E operating procedures and with oxygen imbalance control techniques, would be sufficient to achieve lower NO_x levels than in the first two tests. Additionally, dual duct CEM monitoring was set up to reduce any biases due to the, now rare, oxygen imbalances between the ducts. Results showed however, that NO_x levels were comparable to the first two tests. This could be due to certain effects which tend to negate each other. For example, although the boiler was under better control during the last (fourth) CEM test than during the first two tests, it was also operating at lower loads during the last test than during the first two tests. Lower loads were previously shown to yield slightly greater normalized NO_x concentrations.

In summation, the four 30-day monitoring tests indicated an average NO_x level of 176 ng/J (~ 0.41 lb/MBtu). Typical boiler operation yielded levels of 177-179 ng/J (0.41-0.42 lb/MBtu) for three of the tests, whereas one test using exceptional boiler controls yielded a NO_x level of 160 ng/J (0.37 lb/MBtu).

Note that all four 30-day C.E.M. tests were performed under Modification 2. However, subsequent short term tests performed under Modification 3 revealed that from an operating flexibility point-of-view, Modification 3 hardware is more desireable. As already discussed (Part D, Section F), when at comparable conditions Modification 3 produces slightly higher NO_x emissions than Modification 2 (10-15%, See Figure D-20). However, this increase is offset somewhat by the increased flexibility of Modification 3 which allows the boiler to operate at more favorable low-NO_x conditions not recommended under Modification 2.

IV. CONCLUSIONS

NO emissions (as NO_2) for the four tests (performed under Modification 2) averaged about 180 ng/J (~0.41 lb/MBtu), (well below the 1979 NSPS limit of 260 ng/J [0.6 lb/MBtu] for bituminous coal and the maximum daily average for any day in any of the four tests was about 240 ng/J (0.56 lb/MBtu).

The extractive type continuous emission monitors used in these tests provided quality data for each test (as verified by reference method checks for data quality). However periodic maintenance and calibration was needed to insure continued good data.

PART F

CORROSION TESTING

I. PURPOSE AND STRATEGY

One method often used by boiler operators to decrease NO_x emissions in order to meet the NSPS, is to decrease the amount of excess combustion air being fed to the furnace. This has the added benefit of reducing the amount of hot gases (wasted heat energy) that go up the stack. However, low excess air (LEA) firing could produce chemically reducing environments within the furnace which could lead to increased corrosion. In the Low-NO_x Concentric Firing System (LNCFS) installed on Hunter No. 2, a portion of the combustion air is diverted along the walls (away from the fuel) to blanket the walls with a protective curtain of air. This temporary separation of fuel and air has the added benefit of increasing the amount of time needed for complete combustion. The expected result was slower combustion, lower combustion temperatures, and less NO_x.

The corrosion testing at Hunter No. 2, was designed to quantify corrosion rates within a boiler that complies with NSPS NO_x limits and to allow comparison with rates measured on other boilers.

II. EXPERIMENTAL PROCEDURES AND APPARATUS

Corrosion data was obtained by several methods: corrosion probes, ultrasonic thickness measurements, and furnace gas taps.

A. Ultrasonic Thickness (UT) Tests

The UT method provided the most direct and reliable data on tube wall thickness. In this method, corrosion rates were determined by echo soundings made at about one thousand points at six elevations on all four walls within the boiler. The first set of measurements was made during the September 1981 outage (the same outage in which the LNCFS was installed) and the other set was made during the February, 1984 outage. For additional details of this test method, see Section III-B in Part B of this report.

B. Corrosion Probe Tests

In the corrosion probe method of measuring corrosion rates, the fireside corrosion rates of the furnace walls were not measured directly. Instead, samples of boiler wall materials (called corrosion coupons, or test rings) were inserted into the furnace through inspection doors for relatively short time periods (30-1000 hours) and the boiler wall corrosion rate was assumed to be equal to that of the test samples.

An assembly of five such samples was called a corrosion probe. Three tests were performed, each using five corrosion probes. On the first test, five probes were inserted into the furnace through five inspection doors spread about the furnace and the probes were exposed for 30 hours while being air cooled (from inside) to keep their fireside surface temperature at 650°F (similar to actual water tubes in the furnace). After the 30 hours of exposure, the probes were removed from the furnace and sent to the laboratory for a weight-loss analysis on the coupons. Similarly, the second and third tests each used five new probes that were exposed to the furnace gases at the same locations as those in the first test. However, for these two tests, the exposure times were lengthened to 300 hours and 1000 hours respectively. Additional details of the testing procedure may be found in Section III-A of Part B of this report.

C. Gas Tap Measurements

Some researchers have postulated that low excess air firing (for NO_x control) may lead to chemically reducing environments (low O_2 or high CO) in certain localized areas of the furnace which could result in increased corrosion. Therefore, in addition to the corrosion probe and ultrasonic methods of studying corrosion, samples of furnace gas were withdrawn from along the furnace walls through approximately forty specially installed furnace gas taps and analyzed for possible reducing environments. These measurements were also used in an attempt to evaluate the effectiveness of the LNCFS in blanketing the walls with air, required for both corrosion control and NO_x reduction.

The locations of the gas taps are shown in Figure B-5 (in Part B of this report). The theory behind the gas tap measurements is discussed in Part A, Section IV while the sampling methods are covered more fully in Part B, Section I-B.

III. RESULTS AND DISCUSSION

A. Ultrasonic Thickness Tests

Wall thicknesses were measured ultrasonically at hundreds of locations inside the boiler at six elevations on all four walls. This was done in September, 1981, and again in February, 1984. The difference between the measurements was used to calculate the corrosion rate.

For the 1981 measurements, a chalk line was strung between studs welded to the walls to mark the six measurement elevations (same six elevations on all four walls). Then, at each elevation, the tubes that were selected for measurement were cleaned at the point marked by the chalk line and their thickness was measured at that point.

Table F-1 presents a summary of the 1981 measurements. The top row of data on Table F-1 shows, for example, that for the first elevation (on the hopper slope) on wall no. 1 (the front wall), the average wall thickness of the 27 measured tubes was 0.24784 inches (247.84 mils) with a minimum of 0.2373 inches and a maximum of 0.2583 inches. The range of the values (difference between the maximum and minimum) was 8.5% of the average.

Similarly, the fifth row of data on Table F-1 shows that for the entire first elevation (average of 87 points on all four walls) the average measured tube wall thickness was 0.24502 inches.

For the whole boiler, 595 points were measured (six elevations on all four walls, and the average thickness was 0.24306 inches.

Notice that the elevation summaries (elevation averages) seem to show a trend toward slightly thinner tube walls as one moves higher in the furnace (from the hopper [Elevation A] to Elevation F [just below the nose]). This is not surprising because the gaseous environment in the lower regions (hopper area) of the furnace is more inert than in the burner zone.

Similar data were gathered again in February, 1984, but this time, not only were the measurements made along the chalk lines, but some tubes were cleaned and measured at points just a few inches above and below the chalk lines as well, and some previously measured tubes were not cleaned or measured at all. The reason for this is discussed in Part H of this report. (Incidentally, the chalk lines were strung between the same studs

Table F-1

Tube Thicknesses Measured September, 1981

WALL: 1=FRONT 2=REAR 3=LEFT 4=RIGHT

ELEV	WALL	AVG (inches)	MIN (inches)	MAX (inches)	STD DEV	RANGE (% OF AVG)	POINTS
Level A (in hopper)	1	0.24784	0.2373	0.2583	0.00539	8.5	27
	2	0.23770	0.2316	0.2451	0.00407	5.7	22
	3	0.24678	0.2355	0.2606	0.00657	10.2	19
	4	0.24775	0.2387	0.2586	0.00562	8.0	19
ELEVATION SMRY		0.24502	0.2316	0.2606	0.00689	11.8	87
Level B	1	0.24039	0.2327	0.2532	0.00494	8.5	28
	2	0.24688	0.2287	0.2610	0.00835	13.1	27
	3	0.24740	0.2353	0.2610	0.00696	10.4	21
	4	0.25006	0.2375	0.2686	0.00749	12.4	21
ELEVATION SMRY		0.24580	0.2287	0.2686	0.00789	16.2	97
Level C	1	0.24069	0.2361	0.2481	0.00272	5.0	29
	2	0.24582	0.2295	0.2585	0.00874	11.8	29
	3	0.24149	0.2294	0.2515	0.00588	9.2	22
	4	0.24738	0.2352	0.2567	0.00559	8.7	21
ELEVATION SMRY		0.24372	0.2294	0.2585	0.00678	11.9	101
Level D	1	0.23753	0.2339	0.2417	0.00193	3.3	31
	2	0.24465	0.2300	0.2606	0.00883	12.5	32
	3	0.24477	0.2310	0.2638	0.00688	13.4	23
	4	0.24670	0.2335	0.2564	0.00617	9.3	22
ELEVATION SMRY		0.24305	0.2300	0.2638	0.00742	13.9	108
Level E	1	0.23368	0.2219	0.2396	0.00460	7.6	29
	2	0.24437	0.2195	0.2617	0.00958	17.3	27
	3	0.24215	0.2298	0.2548	0.00611	10.3	21
	4	0.24231	0.2265	0.2584	0.00680	13.2	23
ELEVATION SMRY		0.24033	0.2195	0.2617	0.00825	17.6	100
Level F (just below nose)	1	0.23726	0.2300	0.2435	0.00348	5.7	29
	2	0.24924	0.2322	0.2690	0.00933	14.8	27
	3	0.23722	0.2253	0.2662	0.00722	17.2	23
	4	0.23916	0.2337	0.2484	0.00368	6.1	23
ELEVATION SMRY		0.24085	0.2253	0.2690	0.00820	18.1	102
BOILER SMRY		0.24306	0.2195	0.2690	0.00770	20.4	595

that were used during the 1981 measurements. This insured that the same points were being measured in 1984 as were measured in 1981.)

For each elevation, Table F-2 shows the average values of all thicknesses measured just on the chalk lines for both the 1981 and the 1984 measurements as well as their differences. Note that some of the data from Table F-1 is repeated in Table F-2.

Table F-2 shows that on the average, the boiler tubes lost 1.53 mils of metal over the two years between September, 1981 and February, 1984 or about 3/4 of a mil per year.

The negative value in the last column results from about four corner-tubes which had unusually low readings during the first (Sept, 1981) measurement visit. Had it not been for these anomolies, the data would have fit the trend that seems to be indicated by the other values. That is: low corrosion in the elevations below burners, but increasing corrosion as one moves up into the burner region. Normally, one would expect the highest elevation to show somewhat less corrosion than is seen here, but even the value shown here (3.10) is quite low (about 1.5 mils per year).

In the analysis of the thickness data, the data was examined, and analyzed in many different ways in order to look for trends that might have otherwise been masked and lost among the large volumes of data. Most of the results were inconclusive and therefore have not been included in this report. However, one of the more interesting analyses is presented in the following pages to serve as an example of the type of analyses that were performed. The purpose of this particular analysis was to study the effect of flame impingement on corrosion rates. The boiler tested in this program is not designed to have the flame impinge

TABLE F-2

SUMMARY OF ALL THICKNESS MEASUREMENTS MADE EXACTLY ON THE ELEVATION CHALK LINES

All Values are in Mils. (1 mil = 0.001 inch.)

Elevation	Measured Thickness (mils) September, 1981	Measured Thickness (mils) February, 1984	Loss (mils)
A (Hopper)	245.02	244.94	0.08
B	245.80	243.70	2.10
C	243.72	242.06	1.66
D	243.05	240.54	2.51
E	240.33	240.78	-0.45
F (Just Below Nose)	240.85	237.75	3.10
Whole Boiler Weighted Average	243.06	241.53	1.53

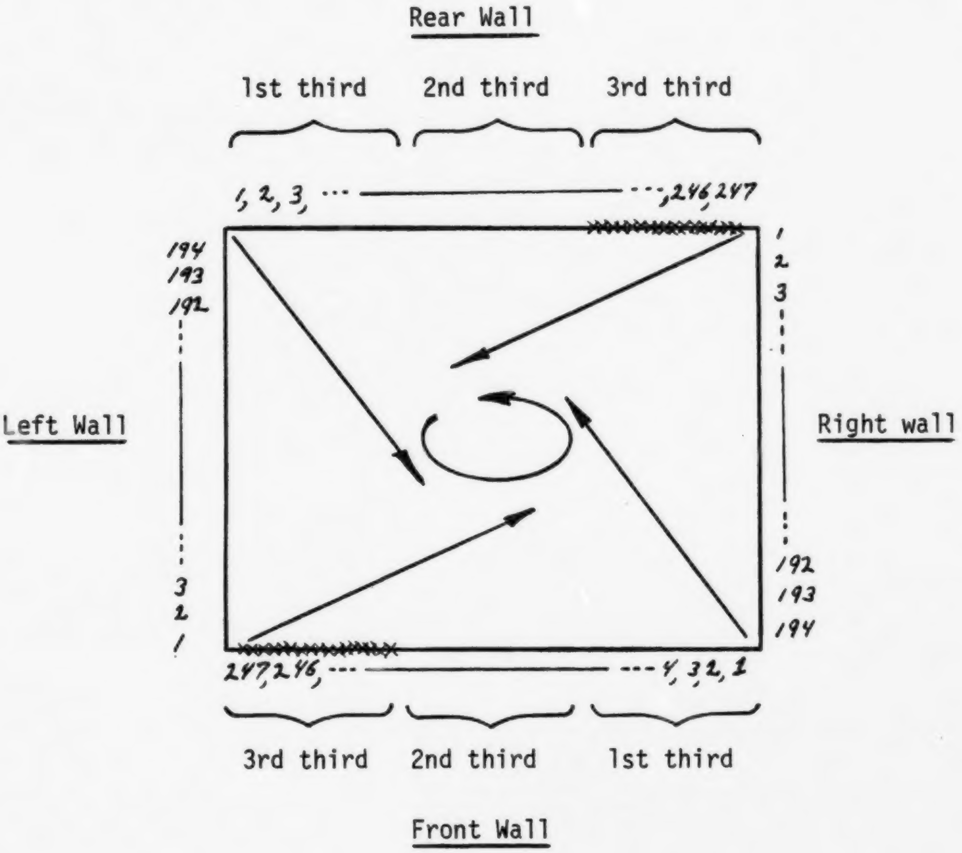
directly on the walls. However the flame's closest approach occurs in the corners just downstream of the burners on the two longest (front and rear) walls. (See Figure F-1.) Therefore, one of the analyses concentrated on data gathered in these corner areas of the burner zone on the front and rear walls.

In the analysis used in this example, only the front and rear walls were considered. These walls are about 25% longer than the side walls (left and right) and are thus more susceptible to corner damage (corrosion) from flame impingement because of the more shallow (glancing) angle that the fuel path makes with these walls when entering the boiler. (See Figure F-1.) Also, because this effect is expected to be strongest in the burner zones, the analysis of the two walls in this example was performed only at Elevations C and D. Furthermore, because the flame is closest to the walls just downstream of each burner (Figure F-1), this corner area (higher numbered tubes) was studied more closely than other regions of the furnace.

For the purpose of this analysis Elevations C and D (the burner levels) on walls 1 and 2 (front and rear) were divided into thirds. The last third, being closest to the downstream side of the burners, was the region where the corrosion rate was expected to be highest. Because of this expectation, more measurements were made in this region (higher numbered tubes in the burner zone of the front and rear walls) than in other areas of the furnace. Table F-3 summarizes the results of this analysis.

The data show that on the average, as expected, the corrosion rates in certain portions of the burner zone were slightly higher than "whole-wall" or "whole-furnace" averages. However, the corner areas where higher corrosion was thought possible, did not show corrosion rates significantly different from other

Figure F-1 Bird's-eye View of Furnace Showing Tube Numbering Scheme and Regions of Expected High Corrosion.


Rear Wall
1st third
2nd third
3rd third
1, 2, 3, ···
···, 246, 247
194
193
192
3
2
1
1
2
3
192
193
194
Left Wall
Right wall
247, 246, ···
··· 4, 3, 2, 1
3rd third
2nd third
1st third
Front Wall

Dimensions: Front and rear walls: 52 feet (247 tubes) across
Left and right walls: 44 feet (194 tubes) across

Notes:

- Tube numbering convention used here is opposite to method used by C-E.
- Region of high expected corrosion is region of closest flame approach (last third [crosshatched] of front and rear walls).

TABLE F-3

THICKNESS AND LOSS RESULTS (IN MILS) FOR EACH THIRD OF THE BURNER ZONE (LEVELS C AND D) ON THE FRONT AND REAR WALLS COMPARED WITH THE SAME DATA FOR ALL FOUR WALLS, AND ALL SIX ELEVATIONS

Average Thickness (or loss) in Mils (Except for the last line, all Data are from the burner zone [Elevations C and D] only)		Data is from Front and Rear Walls Only			All Four Walls
		Sept 1981 (mils)	Feb 1984 (mils)	Loss (mils)	Loss (mils)
First Third (Tubes 1-83)	Elevation C	244.59	242.13	2.46	1.97
	Elevation D	240.11	236.53	3.58	2.74
	Elevations C & D	242.15	233.99	3.16	2.42
Second Third (Tubes 82-165)	Elevation C	243.57	241.67	1.90	1.61
	Elevation D	241.57	240.87	0.70	2.14
	Elevation C & D	242.57	241.24	1.33	1.88
Third (Last) Third (Tubes 164-247)	Elevation C	242.17	240.30	1.87	1.38
	Elevation D	241.55	239.29	2.26	2.66
	Elevation C & D	241.85	239.78	2.07	2.05
All Six Elevations (Whole Wall i.e., all thirds)		242.14	240.83	1.31	1.53

regions of the burner zone. The distinction is even less significant when all four walls are considered (last column on Table F-3). (For simplicity, the intermediate values that make up the last column on Table F-3 have been omitted.) This shows that corrosion by flame impingement in the burner zone is not a problem at Hunter No. 2.

Of course there are endless ways to examine the data. But the important result found in this analysis is that on the average, the corrosion rate in the boiler was about 3/4 of a mill per year and although the highest rates occured in certain areas of the burner zones, these rates were still less than 2 mils per year. No single area of the furnace showed unacceptably high corrosion rates.

B. Corrosion Probe Tests

Three tests were performed using five corrosion probes each. In each test, the 5 probes (each containing 5 coupons) were exposed to the furnace gases for known time periods: 30 hours for the first test, 300 hours for the second, and 1,000 hours for the third (last) test. The exposure locations are covered in Section III of Part B of this report.

After their exposure period, slag deposits were carefully removed from the probes by scrubbing with a mild acid solution and the corrosion rate of each coupon on each probe was determined by weight loss analysis as well as by micrometer measurements of the coupon wall thicknesses. These analyses were performed by C-E, Inc.

These probe studies produced no definitive data to suggest accelerated waterwall wastage as a result of low-NO_x firing conditions. (The average penetration [amount of metal lost on each coupon] was less than 0.001 inches.) Also, analysis of deposits (slag) did not reveal sulfur compounds, such as pyrosulfates and sulfides, usually associated with waterwall wastage.

Each of the 15 temperature-controlled corrosion probes contained five test rings: two fabricated from carbon steel (SA-210) and three from 2-1/4% chromium-molybdenum steel (T-22) with one of the T-22 test rings either protected by a spray coating of Hastelloy C-276 or chromized by a diffusion process.

Table F-4 presents a summary of raw data indicating the weight loss (mg/cm^2) and maximum actually measured thickness losses (by micrometer) for each material type. A more detailed list of data may be found on Tables F-5, F-6, and F-7 (one table for each of the three tests: 30, 300, and 1000 hours). Note that on the tables, the weight loss for each corrosion coupon has been divided through by the appropriate factors (material density, exposed area, exposure time, etc.) to give a loss rate in mils/yr (1 mil = 0.001 inch).

The weight loss data assumes that only one-half of each test ring's outer surface is exposed to the furnace environment. For four of the five probes used in the thirty hour test, the weight loss data for individual test rings showed slight differences between the two materials tested. The 300-hour test showed slightly higher losses for the carbon steel material based on several individual test rings, but a comparison of average weight loss between the 30- and 300-hour tests shows very little change for the carbon steel test rings. The T-22 material had approximately the same average weight loss in both the 30- and 300-hour tests. This may be due to the loss rate of mill scale of one material as compared to another. In the 1000-hour test

TABLE F-4
MATERIAL AVERAGE WEIGHT LOSS AND MAXIMUM MEASURED WALL THICKNESS LOSS

Exposure Time and Location	Weight Loss (mg/cm^2)		Maximum Penetration (inches) (Based on Micrometer Measurements)	
	Material		Material	
	SA-210	T-22	SA-210	T-22
30-Hour				
5th floor	5.5	8.1	0.001	0.001
7th floor front	1.7	7.9	0.001	0.001
7th floor rear	5.4	9.4	0.001	0.001
9th floor	5.2	5.4	0.001	0.001
10th floor	6.1	7.7	0.001	0.001
300-Hour				
5th floor	7.0	8.0	0.001	0.001
7th floor front	7.0	4.9	0.001	0.002
7th floor rear	3.9	8.8	0.001	0.001
*9th floor	3.3	8.6	0.001	0.001
*10th floor	6.7	10.0	0.001	0.001
1000-Hour				
**5th floor	12.3	11.2	0.001	0.001
+++7th floor front	107.5	106.0	0.005	0.005
7th floor rear	12.1	13.7	0.001	0.001
**9th floor	10.9	13.8	0.001	0.001
10th floor	11.8	10.7	0.001	0.001

*Short-term high-temperature excursions. (800°-850°F for <1 hour. Not considered to have affected results much.)

**Short-term elevated temperatures.

+++Overheated (16 hours without cooling air).

TABLE F-5

30-HOUR WEIGHT LOSS DATA

Probe Exposure Location	Coupon No.	Material	Weight Before (grams)	Weight After (grams)	Weight Loss (grams)	Loss (gm/in^2)	Calculated Loss Rate (mils/yr)
9th Floor	193	SA-210	214.4342	214.3173	0.1169	0.030	68.02
	194	T-22	213.0685	212.9430	0.1255	0.032	72.55
	195	SA-210	213.5354	213.3923	0.1431	0.037	83.89
	196	T-22 (Cr)	216.2838	215.9874	0.2964	0.076	172.3
	197	T-22	212.3893	212.2422	0.1471	0.038	86.15
5th Floor	208	SA-210	212.8281	212.9178	0.0103	0.003	6.8
	209	T-22	211.6051	211.4312	0.1739	0.045	102.02
	210	SA-210	213.5509	213.3625	0.1884	0.048	108.83
	211	T-22 (Cr)	212.7858	212.4557	0.3301	0.084	190.43
	212	T-22	212.5533	212.3220	0.2313	0.059	133.76
10th Floor	213	SA-210	212.2341	212.1230	0.1111	0.028	63.49
	214	T-22	210.7845	210.6012	0.1833	0.047	106.55
	215	SA-210	212.4093	212.2143	0.1950	0.050	113.37
	216	T-22 (Cr)	216.2755	216.0391	0.2364	0.060	136.02
	217	T-22	212.4980	212.2958	0.2022	0.052	117.89
7th Floor Front	223	SA-210	213.1451	213.1985	0.0472	0.012	27.21
	224	T-22	212.6252	212.4675	0.1577	0.040	90.68
	225	SA-210	212.5395	212.5028	0.0367	0.009	20.41
	226	T-22 (C-276)	218.3758	217.1568	1.2190	0.309	700.52
	227	T-22	212.4733	212.2362	0.2371	0.061	138.29
7th Floor Rear	228	SA-210	213.9095	213.8523	0.0572	0.015	34.01
	229	T-22	212.5505	212.3144	0.2361	0.060	136.02
	230	SA-210	211.1052	210.8912	0.2140	0.055	124.70
	231	T-22 (C-276)	215.9856	214.3446	1.6410	0.417	945.36
	232	T-22	212.9375	212.7038	0.2337	0.060	136.02
Average of all non-chromized and non-coated coupons							88.26

TABLE F-6

300-HOUR WEIGHT LOSS DATA

Probe Exposure Location	Coupon No.	Material	Weight Before (grams)	Weight After (grams)	Weight Loss (grams)	Loss (gm/in^2)	Calculated Loss Rate (mils/yr)
9th Floor	198	SA-210	213.3082	213.2326	0.0756	0.019	4.31
	199	T-22	211.1471	210.8314	0.3157	0.081	18.36
	200	SA-210	215.3363	215.2484	0.0879	0.022	4.99
	201	T-22 (Cr)	213.9345	213.6447	0.2898	0.074	16.78
	202	T-22	213.0372	212.9177	0.1195	0.031	7.03
7th Floor Rear	203	SA-210	212.7981	212.6941	0.1040	0.027	6.12
	204	T-22	211.9385	211.6568	0.2817	0.072	16.32
	205	SA-210	210.9586	210.8670	0.0916	0.023	5.21
	206	T-22 (Cr)	213.3077	212.9550	0.3527	0.090	20.40
	207	T-22	212.5246	212.3658	0.1588	0.041	9.29
7th Floor Front	218	SA-210	213.8642	213.7996	0.0646	0.017	3.85
	219	T-22	214.0197	213.8032	0.2165	0.055	12.47
	220	SA-210	214.3034	214.0177	0.2857	0.073	16.55
	221	T-22 (C-276)	216.9300	216.3871	0.5429	0.138	31.29
	222	T-22	212.1560	212.1294	0.0266	0.007	1.59
10th Floor	233	SA-210	209.8254	209.6640	0.1614	0.041	9.3
	234	T-22	213.6352	213.4351	0.2001	0.051	11.56
	235	SA-210	214.0433	213.8675	0.1758	0.045	10.20
	236	T-22 (C-276)	220.0497	219.2871	0.7626	0.193	43.75
	237	T-22	212.6297	212.3246	0.3051	0.078	17.68
5th Floor	238	SA-210	212.6867	212.5672	0.1195	0.031	7.03
	239	T-22	213.1406	212.9080	0.2326	0.060	13.60
	240	SA-210	212.1866	211.9572	0.2294	0.059	13.38
	241	T-22 (C-276)	217.8230	217.2024	0.6206	0.157	35.6
	242	T-22	212.1704	212.0009	0.1695	0.043	9.75
Average of all non-chromized and non-coated coupons							9.93

TABLE F-7

1000-HOUR WEIGHT LOSS DATA

Probe Exposure Location	Coupon No.	Material	Weight Before (grams)	Weight After (grams)	Weight Loss (grams)	Loss (gm/in^2)	Calculated Loss Rate (mils/yr)
10th Floor	318	SA-210	213.4665	213.2758	0.1907	0.049	3.33
	319	T-22	213.8697	213.6070	0.2627	0.067	4.56
	320	SA-210	214.7928	214.3931	0.3997	0.102	6.94
	321	T-22 (C-276)	216.2750	215.7617	0.5133	0.130	8.84
	322	T-22	212.3146	212.0402	0.2744	0.070	4.76
9th Floor	323	SA-210	214.3728	214.2476	0.1252	0.032	2.18
	324	T-22	213.0313	212.7487	0.2826	0.072	4.9
	325	SA-210	213.4176	212.9969	0.4207	0.108	7.35
	326	T-22 (C-276)	217.2020	216.6924	0.5096	0.130	8.84
	327	T-22	212.5097	212.0987	0.4110	0.105	7.14
7th Floor Front (Overheated)	328	SA-210	212.9796	210.2601	2.7195	0.700	47.61
	329	T-22	214.1939	211.9401	2.2538	0.577	39.24
	330	SA-210	215.0968	212.3900	2.7068	0.692	47.07
	331	T-22 (C-276)	218.0186	216.4724	1.5462	0.396	26.93
	332	T-22	212.2620	209.1735	3.0885	0.791	53.8
7th Floor Rear	333	SA-210	214.0953	213.8969	0.1984	0.051	3.47
	334	T-22	214.3491	214.0655	0.2836	0.073	4.96
	335	SA-210	214.1235	213.7148	0.4087	0.105	7.14
	336	T-22 (C-276)	219.5250	219.1206	0.4044	0.102	6.94
	337	T-22	210.2878	209.8855	0.4023	0.103	7.01
5th Floor	338	SA-210	212.1519	212.0013	0.1506	0.039	2.65
	339	T-22	213.7985	213.4803	0.3182	0.081	5.51
	340	SA-210	214.5851	214.1185	0.4666	0.119	8.09
	341	T-22 (C-276)	216.9877	216.5196	0.4681	0.119	8.09
	342	T-22	212.3207	212.0749	0.2458	0.063	4.28
Average of all non-chromized, non-coated, and non-overheated coupons							5.27

both materials showed similar weight losses, but these losses were higher than in the shorter tests. From 30 to 1000 hours, the carbon steel material weight loss nearly doubled while the T-22 material compared on the same basis was approximately 1.5 times.

During the 1,000-hour testing phase, the 7th floor front wall probe was exposed to temperatures in excess of 1000°F for 16 hours. (The cooling air to the probe had been inadvertently turned off.) The effects of this overheating are apparent in the weight loss data on Table F-7. Less noticeable effects were evident from the 1000-hour probe on the 5th floor where temperatures above 1000°F were recorded for over 2 hours. The 9th floor 1000-hour probe had also been exposed to high temperatures (above 850°F) for several hours. These high temperature excursions would be expected to accelerate the corrosion rates of the test rings experiencing these conditions.

Micrometer measurements made on the test rings before and after exposure revealed minimal wall losses. These measurements showed that on the average, the wall loss was less than 0.001 inches. However, greater losses were occasionally observed on coated specimens where the coating had spalled or been removed. The test rings exposed to excessive temperatures (overheating) indicated greater wall losses. The increased weight losses observed in the 1000-hour test were not directly confirmed by the micrometer measurements. Such a small maximum penetration with large weight loss probably indicates general attack while a significant maximum penetration and slight weight loss usually indicates pitting.

The use of coatings in this series of exposures was not advantageous as compared to unprotected test rings.

The last lines on Tables F-5, F-6, and F-7 report the average corrosion rates for all non-coated, non-chromized, and non-overheated coupons. That data is shown graphically on Figure F-2 along with the average long-term corrosion rate for the entire boiler as measured ultrasonically. Note that as expected, corrosion rate decreases with time from about 100 mils per year in the short (30-hour) tests to a long term (2-year) rate of less than one mil per year. This supports the theory that new (unconditioned) tubes corrode rapidly at first, but this rate slows down as a protective coating develops on the tube surfaces which inhibits further corrosion.

Deposit Analyses

Chemical analyses of deposits (slag) removed from the probes exposed for 1000 hours are typical of tube external deposits from coal-fired boilers. Insignificant concentrations of corrosion by-products were found in all the analyzed deposits. Examination of these deposits by x-ray diffraction revealed iron oxide and silica as the main compounds. An examination was conducted for sulfur compounds typically associated with tube wastage, but these compounds were not detected. Complete analyses may be found in Appendix VI.

C. Gas Tap Measurements

In evaluating boiler wall areas for reducing environments, low oxygen and/or high CO concentrations can be used as indicators. At the Hunter No. 2 unit, oxygen was used as the primary indicator because there was a fairly consistent localized semi-logarithmic, inverse relationship between oxygen and CO for most of the gas tap readings. This helped in simplifying the analysis. Also, because

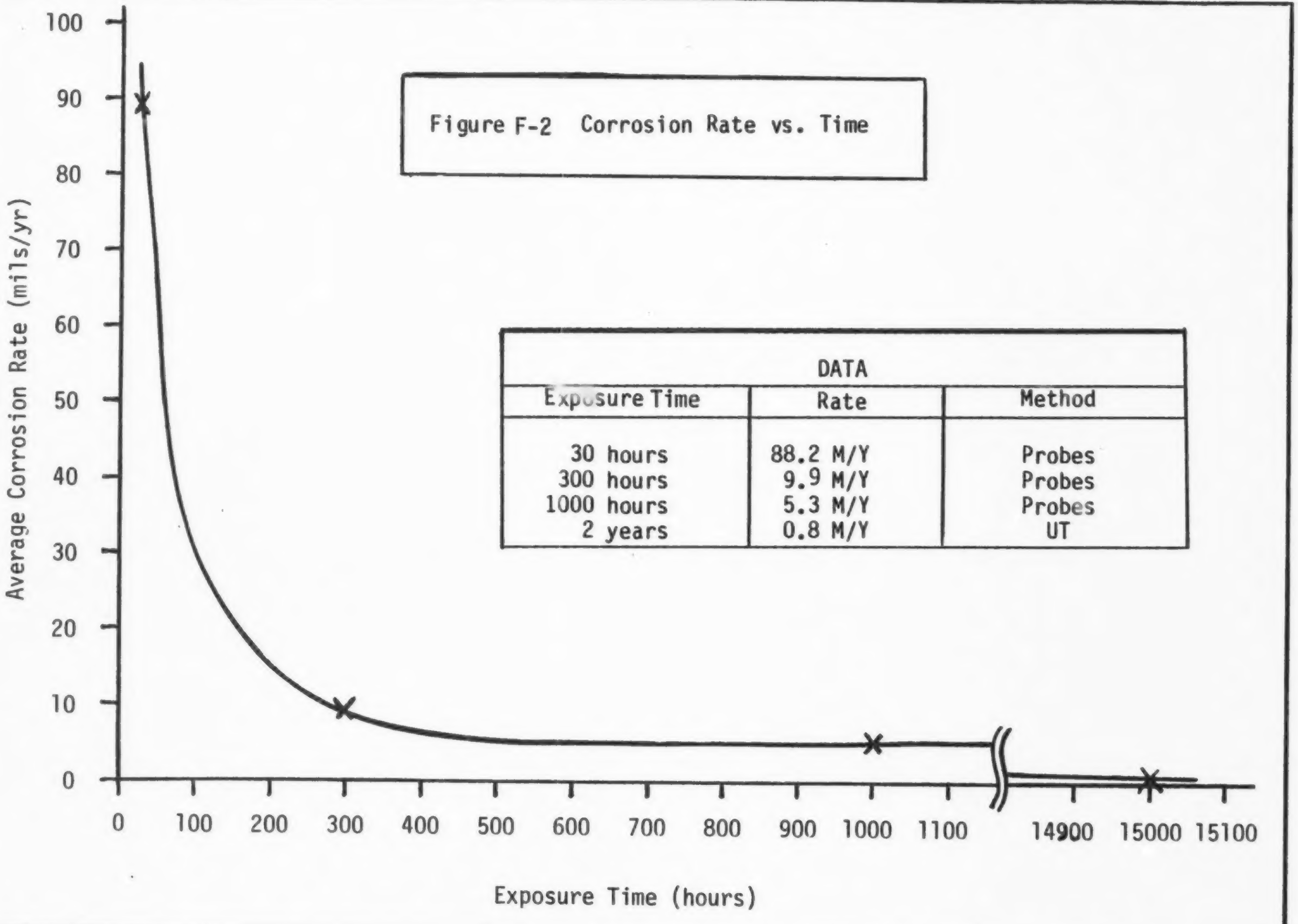


Figure F-2 Corrosion Rate vs. Time

DATA		
Exposure Time	Rate	Method
30 hours	88.2 M/Y	Probes
300 hours	9.9 M/Y	Probes
1000 hours	5.3 M/Y	Probes
2 years	0.8 M/Y	UT

a target O_2 level for potential increased boiler tube corrosion is not readily apparent, the data have been presented here relative to three possible target O_2 levels: 1%, 2% and 5%.

Four complete, and one limited gas tap test were performed. Results from these tests are summarized in Table F-8. Raw data from these tests are presented in Appendix VII.

As an aid in evaluating the gas tap data, the following points should be noted:

- The use of overfire air diverts a significant portion of the auxiliary air to the upper furnace, thereby causing the combustion zone stoichiometry (fuel/air ratio) to increase.
- Excess (flue gas) oxygen levels are an indirect measure of excess air fired and overall oxygen flow rate.
- Windbox-furnace differential pressure (ΔP) is an indirect measure of overall air velocity.
- The auxiliary bank position (i.e., the position of the auxiliary air compartments at all five elevations) gives an indirect indication of the air flow rate into the combustion zone. It must be viewed, however, in association with load, windbox-furnace ΔP, overfire air, and excess oxygen levels.

In full load Test No. 1, there was a significant number of low oxygen (<5%) gas tap readings. The facts that the windbox-furnace ΔP was substantial (5.5 to 6.1 inches w.g.), that the excess oxygen level was moderate (flue gas oxygen level of 4.2%), that

TABLE F-8

HUNTER UNIT NO. 2
GAS TAP RESULTS SUMMARY

Gas Tap Test No.	Corresponding Characterization Test Nos.	Load MW_e	(%) OFA	Offset Angle	Flame Holders	% Excess O_2	Aux. Bank (% Open)	Furnace/ Windbox ΔP (in. w.g.)	Total Data Pts.	No. of Data Pts. in or Above the Burner Zone at Specified O_2 Conditions			Comments
										O_2 <1%	O_2 <2%	O_2 <5%	
1	266-269	400	100	17°	-	4.2	12-30	5.5-6.1	32	0	2	12	1
2	504-508	320	100	8°	✓	3.1	0	3.0-3.4	32	9	16	26	2
3	518-521	430	100	8°	✓	3.5	12	5.0-5.2	34	4	9	21	-
4	531-533	190	0	8°	✓	6.0	10	2.5-3.0	34	0	0	1	-
5	182, 184, 185	420	0	17°,25°,33°	-	6.0	70-100	5.5-6.0	18	0	0	0	3

Comments:

(1) The auxiliary air compartments (aux. bank) were 30% open, except for about an hour at the beginning of the test when the board operator allowed the load to drop to 385 MW_e, and subsequently the aux. bank level automatically decreased to 12% open.

(2) The upper right side of the furnace experienced very low (<2%) O_2 levels.

(3) The 18 data points represent results from Gas Tap locations 17, 18, 19, 23, 24 and 25 (located just above and below the top elevation of burners). These data were taken during three tests run at offset angles of 17°, 25° and 33°.

the overfire air compartments were 100% open, and that the auxiliary air compartments were not open very wide (only 12 to 30%) indicates that much of the combustion air was being diverted to the overfire air compartments, thereby creating a high fuel/air ratio in the burner zone. This suggests that combustion zone stoichiometry may have an effect on wall oxygen levels.

Full load Test No. 3 was run at similar conditions to Test No. 1, except that the effect of the LNCFS was reduced by setting the offset angle to a minimum value of 8°. The fact that Test No. 3 experienced a substantially greater number of low oxygen readings than Test No. 1 may be due to the lower level of excess air fired, but may also be due to the LNCFS having operated somewhat effectively during Test No. 1.

In Test No. 2, the fact that most of the gas taps yielded low O_2 levels was simply due to the closed auxiliary air dampers, caused by the lower load and excess oxygen levels.

Test No. 4 was run at typical half-load conditions, i.e., no overfire air, high excess air levels (6.0% excess oxygen), low windbox-furnace ΔP (2.5 to 3.0 inches w.g.), and auxiliary air dampers nearly closed (10% open). These conditions created a very low fuel/air ratio. As such, only one of the 34 gas tap readings yielded an O_2 level of less than 5%. Because the effect of the LNCFS was reduced by setting the offset angle to a minimum level (8°), this supports the theory that the wall oxygen levels are governed by the combustion zone stoichiometry.

Limited gas tap Test No. 5 was run at full load, but also at conditions which typically create a low combustion zone fuel/air ratio (i.e., no overfire air, high excess air [6% flue gas oxygen], and a high windbox/furnace ΔP [5.5 to 6.0 inches w.g.]). Results show that of the 18 measurements taken, none experienced an oxygen level of less than 5%. While these 18 points represent a total of only 6 different gas tap locations (from 3 separate characterization tests), these results are significant because in each of gas tap tests (No. 1, 2 and 3), at least 1 of these 6 gas tap locations experienced an oxygen level of less than 5%. As in the other four gas tap tests, combustion zone stoichiometry appears to have a significant, if not controlling effect on wall oxygen levels. However, in Test No. 5, the conditions were conducive to greater auxiliary velocities and flow rates such that the LNCFS may also have had an effect on the wall oxygen levels.

Since both the overfire air compartments and the auxiliary air compartments receive their air supply from the same source (i.e., the corner windbox), the use of overfire air diverts air away from the combustion zone. This in turn reduces the air flow rate and velocity through the auxiliary air compartments. Because the use of overfire air increases the fuel/air ratio in the burner zone, the above results suggest that the lower wall oxygen levels which were experienced at higher combustion zone fuel/air ratios may have been due to insufficient auxiliary air flow rates and/or velocities through the LNCFS. Further testing of this should focus on the possibility of separate overfire air and auxiliary air sources.

Regarding the effect of flame holders (Modifications 2 and 3), the majority of the combustion air passes through either the auxiliary air or overfire air compartments. Only a small fraction of the combustion air passes through the burner nozzles, to which the flame holders are attached. Because of this, it is felt that the flame holders should have a minimal effect on wall oxygen levels.

IV. CONCLUSIONS

The corrosion probe and ultrasonic thickness measurement results support the theory that the rate of corrosion decreases as protective coatings develop on tube surfaces during normal use and exposure in the furnace. On the average, the long-term test showed that the corrosion rate was less than one mill per year. However, as will always be the case, some tubes corrode faster than others. But the anomolies that were observed in the data did not seem to fit any recognizable trend. (For example they did not all occur in the same region of the furnace.) While the burner zone exhibited slightly faster corrosion than the whole-boiler average, all regions had rates that were acceptably low. The corrosion rates measured here were about a factor of two lower than similarly measured rates in boilers fired by high-sulfur coals.[F1,F2,F3] ER&E has observed that NSPS low-NO_x operation has not resulted in unacceptable boiler corrosion rates.

Limited gas tap testing at the Hunter No. 2 unit has shown that wall oxygen levels are related to combustion zone stoichiometry. This stoichiometry is greatly affected by total excess air levels and the use of overfire air, and is an indirect indication of auxiliary air flow rates and velocities. An evaluation of the effectiveness of the LNCFS for blanketing the walls with air to overcome low wall oxygen levels (usually associated with high combustion zone stoichiometries) suggests that, under certain conditions, the LNCFS may have been working effectively for this unit. However, more definitive conclusions cannot be reached with the available data.

PART G

SOLIDS TESTING

As discussed in Part A, Section II-A, solids sampling was performed to evaluate the effects of low-NO_x operation on combustion efficiency and other side effects. Unburned carbon in fly ash was one of several parameters used to evaluate combustion efficiency, while particulate testing (mass loadings, particle size distributions and electrostatic precipitator [ESP] performance) was among the side effects evaluated.

Fly ash samples were taken from the ESP hoppers during 32 of the characterization tests. These samples were analyzed (by C-E) for unburned carbon in fly ash. The carbon in fly ash levels were used with the characterization tests' CO levels and other parameters to determine possible trends.

Three complete sets of particulate tests were performed by Entropy Environmentalists, Inc. over a two day period. Mass loadings (in both ducts), particle size distributions (in either duct) and flue gas properties were measured at the inlet to the ESP, while mass loadings (in both ducts) were also measured simultaneously at the outlet of the ESP.

I. Carbon in Fly Ash Results

Results from the (unburned) carbon in fly ash analyses are plotted in Figure G-1 with the supporting data listed in Table G-1. The Figure (G-1) shows that on the average, overfire air tests yielded higher carbon in fly ash levels than non-overfire air tests at comparable loads. Also, non-overfire air tests experienced moderate increases in carbon in fly ash with decreasing loads. This trend was even more significant (steeper slope) when overfire air was

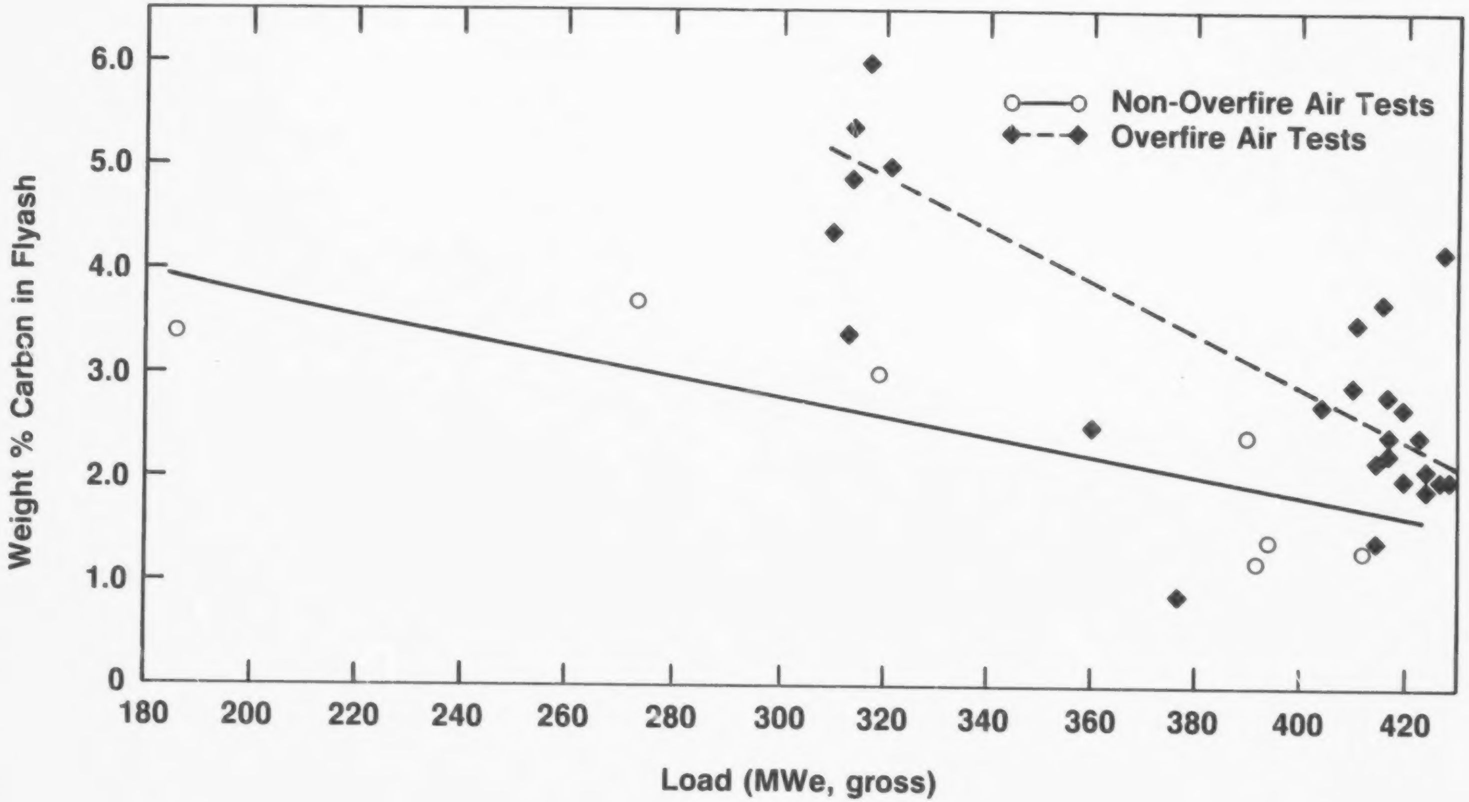


Figure G-1
Effects of Load and Overfire Air on
Carbon in Flyash Levels

TABLE G-1
DATA FOR FIGURE G-1
CARBON IN FLYASH TEST RESULTS

TEST NO.	ELEV	MWE GROSS	FAD	DELTA_P	OFAD	OFFSET	OFAT	BURNER TILT	AUX BANK	AUX 5	AUX 4-5	PERCENT O2	NOX_VPPM	CO_VPPM	CARBON IN FLYASH	NOTES
22	5	392	93	5.00	0	0	0	4	21	60	21	4.62	503	17	1.2	
23	5	394	93	5.00	0	0	0	-1	26	60	26	5.48	496	10	1.4	
24	5	390	93	3.70	0	0	0	2	0	60	0	2.56	355	16	2.4	
127	5	412	100	5.50	0	17	0	5	100	0	0	4.38	397	12	1.3	1
174	5	424	10	5.50	100	25	0	19	53	100	0	5.33	284	140	2.1	2,3
205	5	414	10	5.50	100	25	0	0	56	0	0	4.21	296	11	1.4	
215	5	424	100	5.50	100	25	30	0	40	0	0	3.13	246	493	1.9	
222	5	428	11	5.15	100	25	30	20	56	0	0	3.73	224	2973	4.2	
226	5	416	10	5.40	100	25	30	20	70	0	0	4.88	245	894	3.7	
231	5	417	10	5.35	100	17	0	0	52	0	0	4.38	287	31	2.8	
237	5	420	100	5.45	100	33	0	0	44	0	0	4.58	346	45	2.7	
240	5	415	10	5.45	100	33	0	0	56	0	0	4.86	347	16	2.2	
244	5	411	100	5.45	100	33	0	0	34	0	0	4.69	290	860	3.5	
249	5	410	10	5.25	100	33	0	0	47	0	0	4.78	260	217	2.9	
269	5	420	100	5.95	100	17	30	-23	30	0	30	4.51	257	31	2.0	
322	5	377	100	5.50	100	17	30	-15	8	50	8	3.58	199	64	0.9	
340	5	423	100	5.50	100	25	0	15	24	50	24	3.56	292	81	2.4	
348	5	417	100	5.50	100	17	0	10	22	50	22	3.87	265	144	2.4	4
349	5	417	100	5.50	100	17	0	-10	20	50	20	3.82	249	62	2.3	4
352	5	428	100	5.50	100	17	0	-5	20	50	20	3.20	233	118	2.0	4
353	5	404	100	5.50	100	17	0	-3	20	50	20	4.11	250	61	2.7	5
356	5	360	80	5.50	53	17	0	18	11	50	11	3.14	250	474	2.5	5
520	5	429	100	5.20	100	8	10	22	14	40	14	3.77	280	29	2.0	6
531	3	186	100	3.00	0	8	0	26	10	40	10	6.34	308	26	3.4	6
534	4	273	100	3.50	0	8	0	24	12	40	12	4.53	344	31	3.7	6
535	4	321	100	4.00	100	8	10	25	0	40	0	3.76	305	36	5.0	6
536	4	317	100	4.60	50	8	10	23	0	40	0	3.55	287	27	6.0	6
537	5	314	100	3.40	50	8	10	24	0	40	0	3.11	251	31	4.9	6
538	5	314	100	2.80	100	8	10	23	0	40	0	3.39	265	22	5.4	6
539	4	310	100	4.10	100	8	10	23	0	40	0	3.06	212	55	4.4	6,7
540	4	313	100	4.00	50	8	10	22	0	40	0	2.84	198	169	3.4	6,7,8
605	4	319	100	4.15	0	8	0	0	26	25	25	3.79	319	23	3.0	

NOTES:

1. AUX 2-3 closed.
2. Lower OFA compartment closed.
3. Due to ignition point encroachment near the left rear burner on elevatION 1, the FAD was opened to 100%.
4. AUX 1 were at an 8 degree offset angle and 100% open.
5. AUX 1 at an 8 degree offset angle.
6. Left front burners on elevations 4 and 5, and right rear burner on elevation 5 were at horizontal orientations (0 degrees) due to broken linkages.
7. Bottom four fuel elevations in service.
8. Excess oxygen and CO concentrations fluctuated drastically during this test.

used. These relationships are most likely due to the effect of theoretical air on carbon in flyash levels as explained below.

Burrington, et. al.[G1] showed that carbon in flyash levels (carbon loss) begins to rise significantly once the theoretical air to the fuel firing zone (burner zone) drops below a certain level. This condition does not apply in non-overfire air operation because when not using overfire air, all of the combustion air is introduced into the burner zone and even at very low excess oxygen levels there is still sufficient oxygen for nearly complete combustion. The conventional use of overfire air, however, diverts a considerable portion of the total combustion air to just above the burner zone, thereby reducing the fraction of theoretical air entering the burner zone. At Hunter Unit No. 2, air diversion was somewhat enhanced because the windbox modifications reduced the auxiliary air flow rate into the burner zone. This degree of air diversion was greatest at reduced loads (e.g. ~300 MW_e), where the overfire air compartment dampers were still $\geq$50% open, while the auxiliary air compartment dampers were nearly closed.

Figure G-1 shows that when at full load, carbon in fly ash levels for the overfire air tests were generally greater than for the non-overfire air tests. As explained above, this was due to the effect of decreased combustion air in the burner zone. This effect also explains the high carbon in flyash levels for overfire air tests at reduced loads (~300 MW_e). However, this trend (increasing carbon loss with decreasing loads) for non-overfire air operation, could not be explained by a decrease in theoretical air at the burner zone. Rather, some other effect was responsible possibly due to due to decreased flame temperature or flame stability. Other influences on carbon in fly ash levels at when operating at low loads without overfire air could include changes in fuel/air mixing due to staged combustion. This type of staged combustion could be caused by changes in coal feed size, residence time, combustion temperatures, or other effects which could account for considerable data scatter at a given load.

Typically, the carbon levels for the twenty one full load carbon loss tests ranged between 1.0% and 4.0%; well below the 5.0% maximum acceptability limit set by the utility for fly ash disposal requirements. However, several of the reduced load tests did demonstrate higher levels for the reasons previously discussed.

Regarding CO levels, there appears to be no relationship between CO and unburned carbon levels. This may be due to carbon levels being the result of overall combustion effects, while CO levels were the result of localized combustion effects (spikes).

Because minimal testing (3 tests) of carbon in fly ash was performed during baseline testing, and because these tests were performed without overfire air, it is not possible to compare baseline and post-modification results. However, regarding the effect of low-NO_x modifications on boiler efficiency, there were no substantial differences between baseline and post-modification operation. This is shown in Figure G-2,* and when coupled with the carbon in fly ash results discussed above, indicates that low-NO_x operation does not adversely affect boiler operation.

II. Grain Loading Runs

The total grain loading results (summarized in Table G-2) show that for the conditions of the tests (350-375 MWe), particulate emissions at the ESP outlet were 0.03 pounds per million Btu's of heat input, and the ESP had a collection efficiency of greater than 99%.

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*Boiler efficiency data has been provided by C-E.

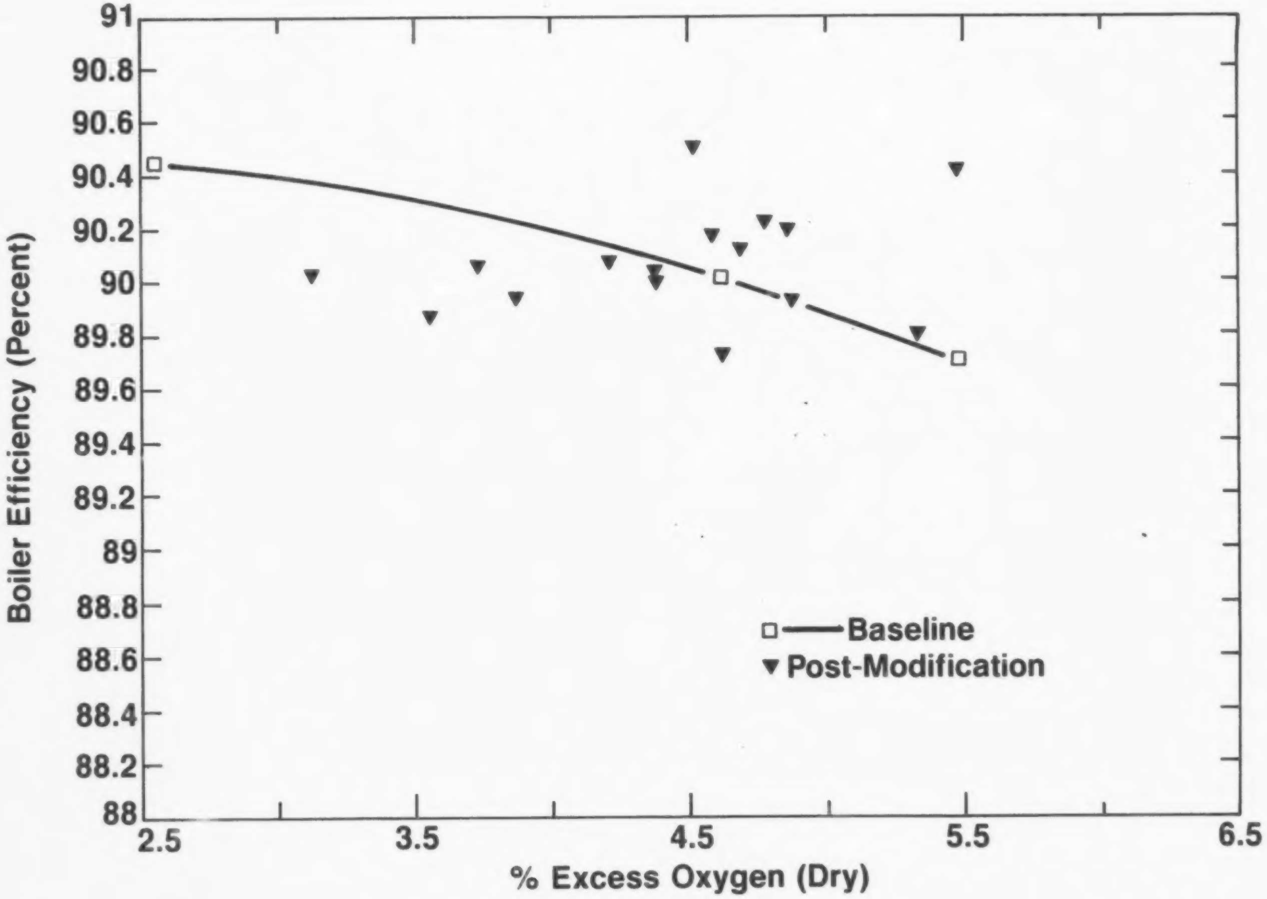

Figure G-2
Excess Oxygen Versus Efficiency

1084-3-341

TABLE G-2

PARTICULATE LOADING IN FLUE GAS -- SUMMARY

Run Date	ESP Inlet		ESP Outlet			ESP Collection Efficiency (%)
	Grains*/DSCF**	Pounds/Hour	Grains*/DSCF**	Pounds/Hour	Pounds/MBtu	
10-13-84 (Morning)	3.281	29,400	0.0130	99.2	0.025	99.6
10-13-84 (Afternoon)	3.526	31,300	0.0081	60.9	0.014	99.8
10-14-84	3.714	30,200	0.0289	208.0	0.052	99.2
Average	3.507		0.0167		0.030	99.5

*7,000 Grains = 1 Pound
**DSCF = Dry Standard Cubic Foot (1 atm, 68°F)

III. Particle Size Distribution Runs

The results of three size distribution runs are summarized in Figure G-3. Test conditions are summarized in Table G-3. For any given particle size (verticle axis), the plots show the amount (in percent -- horizontal axis) of the total mass (of all particles) which is made up of particles smaller (in equivalent aerodynamic diameter - EAD) than the stated size. For example, the plot of Test S2 results shows that about 10% of the particulate mass is made up of particles having an EAD of less than 4 μm. Also, in each case, about 75% (by weight) or greater, of the particles were larger than about 15 μm EAD.

Figure G-3 indicates a significant variation in particle size distribution (PSD) for all three tests, even though operating conditions were fairly similar. A possible explanation is that flue gas particulate matter from coal-fired power plants is actually composed of two types of particles: larger unburned carbon particles and smaller ash particles.[G2] The shape of the PSD curve will depend upon the relative amounts of these two particle types. Parameters which affect the relative amounts of each particle type include the following:

- Coal ash content. (Varied daily at the Hunter Plant).
- Coal size distribution at the burners. (Depends on pulverizer operation which is somewhat dependent upon coal ash content).
- Carbon conversion efficiency. (A function of numerous boiler operating parameters).
- Relative amounts of particulate reaching the ESP compared with amounts which fall into the economizer and main boiler hoppers. (The relative amounts are a function of numerous boiler operating parameters.)

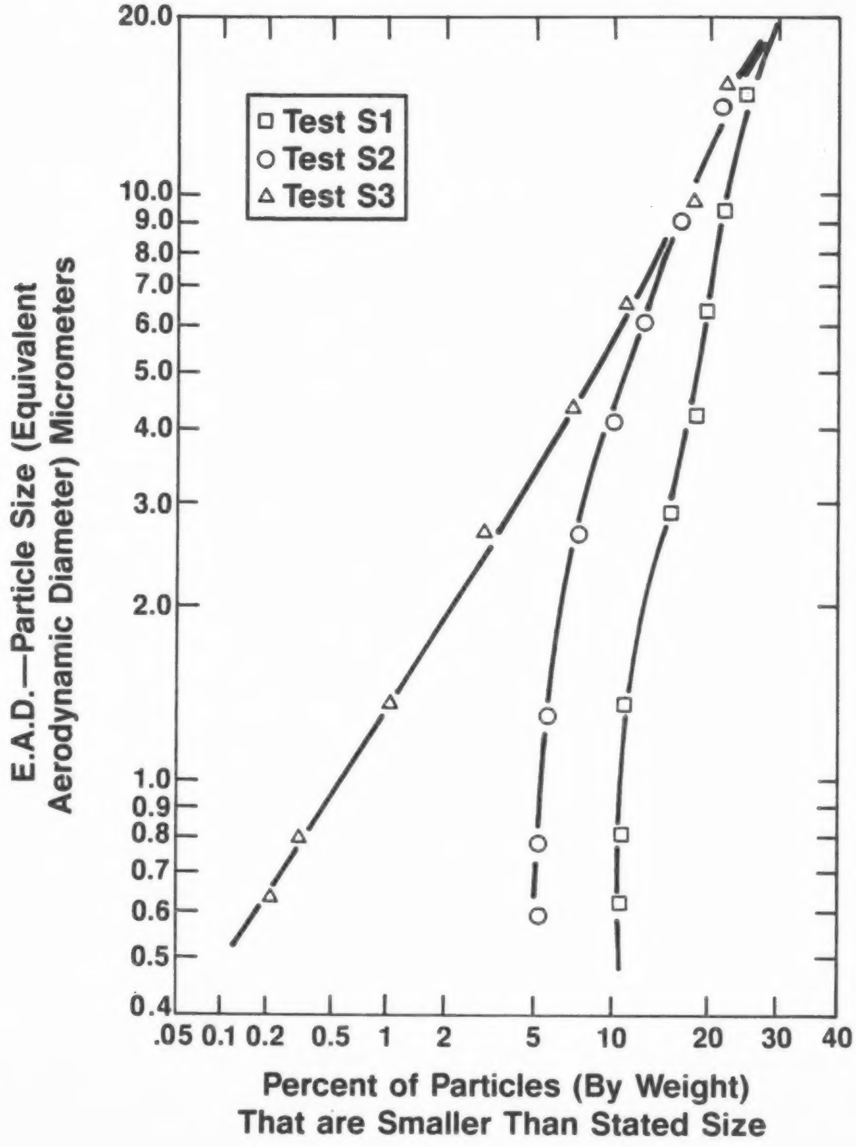

Figure G-3
Particle Size Distribution in ESP Inlet Ducts
(Log EAD vs Probability of Size Occurrence)

TABLE G-3

HUNTER UNIT NO. 2
ESP INLET PARTICLE SIZE DISTRIBUTION (PSD)
TEST CONDITIONS

PSD TEST NO.	DUCT	CHARACTERIZATION TEST NO.	LOAD MW_e	% EXCESS OXYGEN
S1	Right	393	371	3.64
S2	Left	393	371	3.64
S3	Left	398	350	3.24

Sometimes, the PSD curve shape will show a bimodal distribution, (the sum of two different PSD's).[G2] This was the case in tests S1 and S2, where a significant weight percentage of particles (5-10%) had EADS of less than 0.5 µm. This 5-10 weight percent constituted the majority of the total quantity (number) of particulates in both tests. In comparison, results from test S3 appear to follow a nearly log-normal progression. The difference between these two distinct PSD's is likely due to differences in several of the parameters discussed above. One added fact that has a bearing on these results is that test S3 was run a day after tests S1 and S2, and although an attempt was made to repeat the conditons of the previous day, several boiler conditions may have changed over that time period without being noticed.

Finally, with regard to the size distribution data, one should consider the effects of the heavy grain loadings on the PSD results. For example, because of the heavy grain loading, the sampling time had to be kept short (10 minutes) in order not the overload the impactor stages of the sampling equipment. The short sampling times meant that the set-up time (needed to establish isokinetic conditions) may have been a significant portion of the total sampling time. Also, even with the short sampling times, some of the stages overloaded anyway (> 10 mg per stage) and could have produced somewhat biased results.*

IV. CONCLUSIONS

The analyses of particulate matter (PM) show no adverse effects on PM emissions while using CM for low-NO_x. Figure G-3 shows that more than three quarters (by mass) of the PM entering the ESP has a size

---

*Overloading leads to re-entrainment which would bias the results to show smaller particles than is truly the case.

(EAD) greater than 15 μm. These large particles are easily removed from the gas stream and overall, the ESP operated with a collection and removal efficiency of more than 99%. Consequently, the ESP outlet (scrubber inlet) loading was 0.03 pounds per lb/MBtu.

Operation of the boiler under low-NO_x conditions does not appear to affect boiler operation. Boiler efficiency levels of about 90% were maintained, full-load carbon-in-fly ash levels were under the utility's 5.0% requirement for flyash disposal, and the ESP was able to achieve high particulate removal efficiencies.

PART H

QUALITY ASSURANCE

In order to ensure that the data gathered under this program was of acceptable quality, certain quality control and quality assurance (QA/QC) procedures were implemented. For the gaseous data, the QA/QC measures included certification of calibration standards as well as frequent recalibration of emission monitors. For the particulate sampling system, QA/QC steps included careful measurement and calibration of sampling nozzles and sample metering systems. Finally, for the corrosion measurements, the QA/QC procedures included repeatability tests.

I. Gaseous Emissions Testing

In the gaseous emissions tests both flue gas and furnace gas composition were monitored by extractive CEMs. Data quality was dependent on four key parameters:

- Accuracy of the calibration standards ("cal gases").
- Quantity of data gathered.
- Stability (drift speed) and frequency of recalibration of the CEMs.
- Absence of leaks in the sampling system.

For each instrument, several calibration gases were used to zero and span its measurement range. When setting up each gas analyzer, calibration gas (a gas of known concentration--for example 4.5% O_2)

was fed to it, and the instrument's output was adjusted using the real-time data acquisition/computer system CRT until it read the same as the calibration gas standard. The concentration of each calibration gas was measured in the laboratory (usually by gas chromatography) using standards that were traceable to the National Bureau of Standards (NBS). After mixing, but prior to analysis of each calibration gas, the gas was allowed to stand for several days to ensure that equilibrium was reached and that its composition was stable. Each calibration gas mixture was used before the expiration date of its analytical certification.

The accuracy of test results was greatly enhanced by the data acquisition/computer system. Utilizing a Macsym II™ computer (made by Analog Devices), the data acquisition system was programmed to take a full set of gaseous emissions data every 2 seconds. Therefore, by sampling each probe assembly (3 sample points) for one minute, the resulting gaseous data for each component (NO_x, CO, etc.) was a composite of 360 separate pieces of data (1 minute per probe assembly, 4 probe assemblies, three sample points per probe assembly).

The analyses and the stability of the calibration gases were further checked in the field by comparing old gases with new ones each time a gas cylinder was replaced. In this procedure, a CEM would be calibrated with an old calibration gas just before the gas cylinder was replaced. Then the new calibration gas would be measured using the CEM that was calibrated on the old gas. If the reading of the new gas was within ± 5% of the concentration certified by the laboratory, then both the old and new gases were tentatively accepted at that time. These procedures insured the accuracy of the calibration gases.

Another requirement for quality CEM data was the stability (drift) of the monitor between calibrations. Span drifts of less than ± 5%

(of the calibration gas concentration) between calibrations were considered acceptable. Compliance with this goal was accomplished by frequent calibrations so that regardless of any particular instrument's drift rate, it was recalibrated often enough to ensure that reading would always be within ± 5% of the true reading.

The final requirement for quality CEM data was the absence of leaks in the sampling system. A leak on the vacuum side of the sampling pump would pull air in with the sample and dilute it. Such dilution could occur only on the vacuum side of the pumps and was thus minimized by placing the pumps as close as possible to the sampling location. If a leak did occur on the vacuum side of the pump, it revealed itself in the form of a high oxygen reading on the O_2 monitor or as a slight flow rate or pressure reading in the analytical van when the system was dead-ended. Leaks were then quickly discovered and corrected.

For example, when sampling a flue gas containing 2% oxygen, a leak equal to just 10% of the sampling rate would cause the oxygen monitor to show about 4%. Because four separate sampling systems were used to bring flue gases to the analyzers, any one system containing a potential leak could be discovered quickly by comparing the four O_2 readings with each other.

Finally, even the smallest leaks were factored out by computer-correcting all measured gas concentrations (other than O_2) to a standard dilution (3% O_2).

II. Solid Species Testing

A. Fly Ash Sampling

Fly ash samples were taken by either Exxon or C-E personnel at the end of each specified characterization tests in order to analyze for unburned carbon. To ensure that the fly ash was from only the test under consideration and not from a prior tests, the following procedure was followed. Test conditions were set and the test was started. Then after about 20 minutes, the fly ash sample container was emptied and replaced. Finally, as the test was continued, the sample container was filled and then removed (with its sample) about twenty minutes later. This required longer characterization tests run times than was normally practiced.

Fly ash samples were then sent to C-E for chemical analysis. A large sample (~1 liter) was taken each time in order to reduce any analytical biases.

B. Particulate Loading and Size Distribution

The accuracy of the particulate loading and size distribution measurements is heavily dependent upon the accuracy of the sampling rate and stack gas velocity measurement equipment. The following equipment or calibrated standards were used in the measurements.

- Dry gas meter - used to measure sampling rate.

  Each dry gas meter was calibrated against a spirometer (at several different flow rates) and was found to be accurate within 1%.

- Orifice meter - used to measure sampling rate (required for isokinetic sampling).

  Each orifice plate coefficient was calibrated at several different flow rates to allow the instantaneous determination of sampling rates during each field test.

- Nozzle Diameter - used to determine sampling velocity.

  The diameter of the sampling nozzle is used with the sampling rate data to determine the velocity of the sample as it enters the nozzle. This allows the sampling rate to be adjusted as necessary during sampling to insure that the nozzle gas velocity equals the duct gas velocity so that the sampling system does not disturb the system being sampled. This ensures that a representative sample will be obtained. All nozzle diameters were measured at least eight times (along several different axes) and no reading on any nozzle was more than two percent away from the average.

III. Corrosion Monitoring

In the corrosion study, tube wall thicknesses were measured to the nearest ten-thousandth of an inch (or four significant digits) in order to detect small thickness changes (1 or 2 mils) in a relatively large base value (about 250 mils).

In the following discussion, the reader should keep in mind the fact that all measured thicknesses were about 250 mils. Previous experience[H1,H2,H3] has shown that when measuring a single point on a tube with a rough surface, the precision of any one reading may be off from the true value by as much as one mil or more. The problem is compounded when one adds in the uncertainty of finding the same point on two successive readings; especially when those readings are two years apart. Of course this is not acceptable when thickness changes of just one or two mils are being examined. Fortunately, by averaging large amounts of data, the individual random errors can be averaged out and the accuracy is very much improved. The more data that is averaged, the higher the accuracy of the result. This explains some of the anomalies in the thickness tables presented in Section III-A of Part F of this report. The reader will note that as more data points make up tabulated values, the trend lines become smoother.

Duplicate measurements of groups of about fifteen data points each show that it is not unusual for repeat measurements of individual tubes to differ from the original measurement by a mil or more. But the average value obtained for the group is repeatable within about 0.2 or 0.3 mils. Hence, when performing data analysis, thickness changes at a single measurement point should not be heavily weighted. Instead, the average change for a group of points (in the same region of the furnace) is far more significant. In fact, when considering one data point at a time, it is not unusual to see negative thickness changes. Of course, such values, for the reasons cited above, are insignificant and will diminish when averaged into large groups of data. These claims are supported in Table H-1 which presents the results of duplicate readings from about fifty measurement locations. Each duplicate reading was made by the same operator using the same instruments as in the original reading, and each duplicate reading was made within a day or two of the original reading. (Of course the original measurement results were not made available to the instrument operator as the duplicate measurements were being made.)

The table shows that under these conditions, repeat measurements of a single point in the boiler may differ from each other by more than two mils and differences of about one mil are not unusual. However when as few as fifteen measurements are averaged, the repeatability (on the average) is much improved. In fact, when all 47 points on the table are considered, the average repeatability is within about 0.13 mils (0.0013 inches) or about 1/2% of the average value. The data shown on Table H-1 is typical. However, because the corrosion losses being considered in this report are so very

TABLE H-1

COMPARISON OF DUPLICATE THICKNESS MEASUREMENTS
(Made in February, 1984 by the same operator using the same instrument)

Indentification of Measured Location				First Reading	Second Reading	Difference = First-Second
Wall	Elevation	Tube No.	Top, Middle, or Bottom Position	(mils)	(mils)	(mils)
Left	Level B	121	T	246.9	244.8	+2.1
		121	M	250.0	249.3	+0.7
		121	B	246.9	245.7	+1.2
		133	M	254.0	253.5	+0.5
		139	M	235.4	234.4	+1.0
		145	T	245.4	246.6	-1.2
		145	B	251.9	252.1	-0.2
		151	M	246.2	248.0	-1.8
		163	M	236.2	236.4	-0.2
		175	T	251.9	251.5	+0.4
		175	M	251.0	250.0	+1.0
		175	B	244.9	244.9	0.0
		187	T	237.7	236.7	+1.0
			B	235.7	236.9	-1.2
						+0.236
	Level C	119	T	246.2	246.5	-0.3
		119	B	249.5	249.4	+0.1
		125	T	256.3	255.9	+0.4
		125	M	253.0	251.7	+1.3
		125	B	253.5	252.7	+0.8
		131	M	239.9	240.0	-0.1
		137	T	256.0	256.0	0.0
		137	B	245.7	245.5	+0.2
		149	T	238.5	239.5	0.0
		149	M	243.1	244.9	-1.8
		149	B	251.6	251.5	+0.1
		161	M	241.9	242.4	-0.5
		173	T	251.4	251.4	0.0
			B	250.8	250.5	+0.3
		179	M	240.8	242.0	-1.2
		185	M	240.9	241.5	-0.6
						-0.081
Right	Level C	104	T	250.7	249.9	+0.8
		104	B	250.4	250.3	+0.1
		110	M	238.4	239.5	-1.1
		122	T	247.6	247.5	+0.1
		122	M	250.2	251.2	-1.0
		122	B	243.1	242.2	+0.9
		134	T	250.1	249.7	+0.4
		134	B	239.5	240.1	-0.6
		140	M	253.9	251.8	+2.1
		146	M	244.9	244.3	+0.6
		152	T	247.6	247.3	+0.3
		152	M	241.7	242.1	-0.4
		152	B	247.3	247.1	+0.2
		164	M	246.0	245.8	+0.2
		170	T	241.6	241.8	-0.2
		170	B	250.6	250.1	+0.5
		182	M	247.1	245.9	+1.2
						+0.241
UNWEIGHTED AVERAGE						+0.132

small relative to the base values, a single tube with a large loss could easily influence the average of even a large number of data points. An example of this was pointed out on Table F-2 in Section III-A of Part F of this report.

Another important consideration is that the corrosion rate may be influenced by the process used to measure it. In the ultrasonic method of measuring tube wall thicknesses, the slag and other surface deposits (mill scale etc.) must be cleaned from the outside surface of the tubes before they can be measured. However, these surface layers (oxides, slag, etc.) may act as protective coatings that inhibit further oxidation, sulfidation, or other precursors to corrosion. The result is that a freshly cleaned tube (such as one that was prepared for thickness measurements) may corrode faster than a pre-conditioned tube that is left alone.

In order to quantify this effect, on certain tubes, two points (one a few inches above, and the other just below the point of interest) were measured during the February, 1984 visit. Generally, if the point of interest (the one on the chalk line discussed earlier) had not been interfered with (for example by cleaning it for measurement in September, 1981), then its thickness (in February 1984) should equal the average of the points just above and below it. But, for reasons already discussed (occasionally large random errors), this conclusion would hold true on the average, only when large groups of data are considered. If, on the average, the conclusion does not hold, then the difference must be due to accelerated corrosion on the points that were cleaned for measurement in September 1981. A table of such data could be used quantify the effect. Table H-2 was assembled for that purpose.

The table considers only a portion of the data that were reported in Section III-B of Part F of this report. Specifically the data used to compile Table H-2 include only those locations for which

TABLE H-2

EVALUATION OF MEASUREMENT BIAS

COMPARISON OF DIRECTLY VS INDIRECTLY MEASURED DATA*

Data Source Front and Rear Walls		Direct Measurements (Middle Points Only)	Indirect Measurements (Average of Top and Bottom Points)	Difference (Indirect-Direct)
Elevation	Tube Nos.	mils	mils	mils
A	1-247	241.95	242.78	0.83
B	1-247	243.17	243.13	-0.03
C	1-83	245.20	245.55	0.35
C	82-165	241.42	243.99	2.57
C	164-247	238.94	239.19	0.25
D	1-83	242.14	244.20	2.06
D	82-165	241.42	241.84	0.42
D	164-247	242.96	243.22	0.26
E	1-247	241.95	243.78	1.83
F	1-247	239.94	240.95	1.01
UNWEIGHTED AVERAGE				0.955

* In September of 1981 the tubes reported on this table were measured at the location of interest (along the chalk lines) only. Then, in February of 1984, these same locations were remeasured, but, for each tube location reported on this table, two additional points were also measured -- one just above, and one just below the chalk line (by a few inches). The average thickness of the top and bottom points should equal to the thickness value at the middle point. If it does not, then on the average, the difference may be due to the measurements' built-in bias as explained in the report.

all three points (top, middle, and bottom) were measured in February, 1984. The "T" and "B" positions were measured for the first time in February, 1984, while the "M" positions had already been cleaned and measured once before (in September, 1981) and might have a built-in bias (accelerated corrosion rate) as a result of the cleaning procedure used for the previous measurements. Table H-2 shows that on the average, the previously measured point ("M") is about one mil thinner on its second reading than the average of the two surrounding points (T and B).

The results presented in Section III-A, of Part F of this report have not been adjusted to reflect this bias for two reasons. First, by not factoring out the bias, a measure of conservatism is added to the results. The second reason is that during the September 1981 measurements, many of the tubes were cleaned excessively prior to measurement. Thus the differences reported on Table H-2 may be partially due to metal removed in the September, 1981 measurements rather than accelerated corrosion after the measurement. This effect, however, was minimized by remeasuring those same points (to the extent possible) in February of 1984 while taking extra care not to remove any metal from the tubes' surfaces as they were cleaned (by motorized wire brushing wheel) in preparation for the measurements.

IV. Gas Tap Measurements

The goal of the gas tap measurements was to detect large differences in oxygen and CO levels along the furnace walls and to relate these to the effectiveness of the LNCFS, at different operating conditions. Because very precise readings were not required, rigorous calibration procedures (as in the case of the characterization testing) were not followed.

The two gas tap instruments were initially calibrated in the analytical van. The MSA Model 1000 measures oxygen (0 - 25%) and carbon monoxide (0 - 2000 vppm). Its oxygen scale was calibrated with nitrogen for the zero, and ambient air for the span (21% O_2) gas. The CO scale was adjusted using nitrogen for setting the zero point, and using several CO calibration gases (779 vppm and 1400 vppm) for span adjustment. The Sun Instrument (0 - 10% CO) was calibrated using internal electronic calibrations, plus a 1.5% CO span gas.

Once the MSA instrument was initially calibrated it was normally re-calibrated once during the test and once after the test, unless a filter cartridge had to be replaced. If the oxygen scale was found to be accurate within ±0.5%, then all oxygen data was considered acceptable. If the CO instrument readings were within 100 vppm, then they were also accepted. Regarding the Sun Instrument, electronic re-calibrations were performed after every reading. In addition, calibration using calibration gas was performed after each test. If the calibration yielded results that were accurate within ±10% of the true value, then the results were considered acceptable.

During testing, certain precautions were taken to protect the MSA instrument's CO detection cell from being exposed to very high CO concentrations (> 2000 vppm). First, the Sun Instrument was used to detect preliminary CO levels. If the levels were $\geq$ 1,500 vppm, then the Sun instrument's CO reading was used. For lower CO readings the MSA instrument was used. The MSA instrument was always used to measure O_2 levels, however its CO sensor was often bypassed when CO levels were known to exceed its range.

Additionally, because samples were being extracted from a very harsh environment (i.e., one including high levels of combustible and corrosive species), close attention was given to the particulate and condensate filters to insure that they were not over loaded. Both instruments were equipped with such filters and the filter media was replaced as needed.

PART I

REFERENCES

PART A:

A1) J. M. Levy, et al., Combustion Research on the Fate of Fuel-Nitrogen Under Conditions Of Pulverized Coal Combustion. MIT. EPA-600/7-78-165. NTIS Report No. PB-286 208. 1978. Page 5.

A2) J. J. Marshall, A. P. Selker. The Role of Tangential Firing and Fuel Properties in Attaining Low NO_x Operation for Coal-Fired Steam Generation. Fossil Power Systems--Combustion Engineering, Inc. Windsor, Connecticut. Presented at the EPRI NO_x Control Technology Seminar. Denver, Colorado. November 8 and 9, 1978.

A3) S. L. Chen, M. P. Heap, and D. W. Pershing. Energy Environmental Research Corporation. Irvine, California. Bench Scale NO Emissions Testing of World Coals: Influence of Particle Size and Temperature. From the Proceedings of the 1982 Joint (EPA/EPRI) Symposium on Stationery Combustion NO_x Control. Volume 2: Fundamental Studies and Industrial, Commercial, and Residential Applications. Prepared by the Electric Power Research Institute. Palo Alto, California. EPRI Report No. EPRI CS-3182. July 1983.

PART B:

B1) A. R. Crawford, M. W. Gregory, E. H. Manny, Magnitude of SO_2, NO, CO_2, and O_2 Stratification in Power Plant Ducts. Exxon Research and Engineering Company. EPA Report No. EPA - 600/2-75-053. September, 1975. Prepared under EPA Contract No. 68-02-1722.

B2) EPA Method 17 - Determination of Particulate Emissions from Stationary Sources (In-stack Filtration Method). Code of Federal Regulation (CFR), Title 40 "Protection of the Environment", Part 60 "Standards of Performance for New Stationary Sources" (NSPS), Appendix A "Reference Methods". Revised July 1, 1982 Pgs. 498-515.

PART E:

E1) Code of Federal Regulations (CFR), Title 40 "Protection of the Environment", Part 60 "Standards of Performance for New Stationary Sources" (NSPS), Appendix B "Performance Specifications". Revised July 1, 1982. Pgs 559-580.

PART F:

F1) A. R. Crawford, E. H. Manny, and P. S. Natanson. Evaluation of Tubewall Corrosion Rates on a Coal-Fired Utility Boiler Using Staged Combustion for NO_x Reduction. Prepared for EPA by Exxon Research and Engineering Company. EPA Project Officer: R. E. Hall. ER&E Report Number: EE.8DB.83. EPA Report Number: EPA-600/7-83-054. NITS Report Number: PB84-118231. 330 pages. October 1983.

F2) Paul S. Natanson. Long-Term Optimum Performance/Corrosion Tests of Combustion Modifications for Utility Boilers. Host Site: Columbus and Southern Ohio Electric Company, Conesville No. 5. Prepared for EPA by Exxon Research and Engineering Company. EPA Project Officer: David G. Lachapelle. ER&E Report No: EE.7DB.83. EPA Report Number: EPA-600/7-83-049. NTIS Report Number: PB84-102698. 350 pages. September 1983.

F3) Paul S. Natanson. Long Term Optimum Performance/Corrosion Tests of Combustion Modifications for Utility Boilers. Host Site: Louisville Gas and Electric Co., Mill Creek No. 3. Prepared for EPA by Exxon Research and Engineering Company. EPA Project Officer: David G. Lachapelle. ER&E Report Number EE.9DB.83. EPA Report Number: EPA-600/7-84-003. NITS Report Number: PB84-128966. 286 pages. January 1984.

PART-G:

G1) Richard L. Burrington, John D. Cavers and Ambrose P. Selker. Technology For Tangentially Fired Utility Boilers Burning Western U.S. Coal. Prepared for EPA by Combustion Engineering, Inc. EPA Project Officer: David G. Lachapelle. EPA Report Number: EPA-600/7-77-117. 312 pages. October 1977.

G2) H. E. Hesketh. Fine Particles In Gaseous Media. Ann Arbor Science. 1977. p. 4.

PART H:

H1) Same as Reference F1.

H2) Same as Reference F2.

H3) Same as Reference F3.

PART J

APPENDIXES

I. CONTROL ROOM BOARD DATA (SAMPLE DATA SHEETS)
II. FLUE GAS DATA (SAMPLE DATA SHEETS)
III. CONVERSION FACTORS, F FACTORS, AND SAMPLE CALCULATIONS
IV. PORTIONS OF METHOD 17 AND PSD REPORTS
V. 30-DAY CEM TEST SUPPLEMENTAL INFORMATION
VI. COAL AND SLAG ANALYSIS
VII. FURNACE GAS TAP DATA

APPENDIX I

CONTROL ROOM BOARD DATA (SAMPLE DATA SHEETS)

Extensive boiler operating data were recorded during each of the hundreds of characterization tests reported in Parts C and D of this report. These data include a record of about 100 operating parameters (load, steam temperature, burner tilt, etc.) to specify the boiler's operating mode and condition as completely as possible during each test. These data have already been discussed in the text of this report but are too voluminous to present in their entirety herein. Instead, the control room raw data sheets from tests 60 through 64 are presented here as an example of the boiler operating data that were gathered during each test.

APPENDIX I

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UTAH POWER AND LIGHT COMPANY (UP&L)
HUNTER GENERATING STATION, UNIT #2
CASTLE DALE, UTAH

PG 1 OF 8

OPERATING DATA (CONTROL ROOM BOARD AND DATA LOGGING COMPUTER)

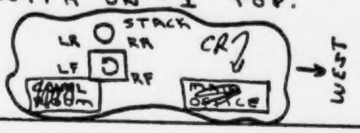
TEST NUMBER	60	61	62	63	64
DATE	8-18-81	8-18-81	8-18-81	8-1881	8-18-81
TIME (24 HOUR MILITARY CLOCK)	00:20	01:56	04:02	04:40	05:40

SUMMARY (LOG #73)

DESCRIPTION	UNITS	DATA* SOURCE					
PURPOSE			LIKE TEST #52, BUT W/ BOTTOM MILL OFF.	LIKE #53 BUT BOT MILL OFF MED LOW XS AIR	HIGH XS AIR. LIKE #54, W/ BOTTOM MILL OFF	~~C~~CLOSED BOT AUX & OPENED OFA TO 60% (LIKE #56 W/ BOT MILL OFF)	NORMAL AIR OFA = 40% LIKE #51 BUT BOT MILL OFF
LOAD (GEN GROSS)	MW	2002	302	301	299	298	297
EXCESS AIR	L·N·H	—	NORMAL	MED-LOW	HIGH	HIGH	NORMAL
MILLS IN SERVICE		CR	1,2,3&4	1,2,3,&4	1,2,3,&4	1,2,3,&4	1,2,3,&4
OFA DAMPERS TOP	% OPEN	CR	0	0	0	60	40
OFA DAMPERS BOT	% OPEN	CR	0	0	0	60	40
TILTS OFA NOZZELS	DEG UP	LOCAL	0	0	0	0	0
TILTS BURNERS	DEG UP	CR	0	0	0	0	0
MAIN STEAM FLOW	KP/Hr	9083	2058	2044	2091	2050	2050
THROTTLE STEAM TEMP	°F	2001	1009	1013	1006	1002	1002
THROTTLE STEAM PRES	PSIG	2000	2416	2403	2398	2403	2403
TURB 1ST STG PRES	PSIG	2023	1240	1232	1229	1232	1232
WINDBOX / FURNACE: ΔP	IN H_2O	CALCULATED	4.0	3.2	~4.8	~4.0	~3.6
FUEL AIR DAMPERS	% OPEN	CR	~100	~100	~100	~100	~100
AUX AIR DAMPERS	% OPEN	CR	0	0	8	0	0
OPERATOR'S NAME	—	—	ED	ED	ED	ED	ED
THIS DATA RECORDED BY	NAME	—	PSN	PSN	PSN	PSN	PSN

BOILER GEOMETRY
#1 = RIGHT = WEST
(ALL ID NUMBERS START IN THE NORTH-WEST CORNER)
BURNERS ARE NUMBERED 1-5 WITH ON #1 TOP.

* CR: CONTROL ROOM
NA: NOT AVAILABLE



]

UP&L HUNTER #2 OPERATING DATA

PG 2 OF 8

TEST No.	60	61	62	63	64
DATE	8-18-81	8-18-81	8-18-81	8-18-81	8-18-81
TIME (MILITARY)	00:20	01:57	04:04	04:44	5:49

FLOW RATES (LOG 73)

COAL FLOW	TOTAL	KP/Hr	1160	263	268	262	258	256
	FDR 1	KP/Hr	1185	66	66	65	64	63
	FDR 2	KP/Hr	1186	66	67	65	64	64
	FDR 3	KP/Hr	1187	67	67	66	65	64
	FDR 4	KP/Hr	1188	66	67	65	64	64
	FDR 5	KP/Hr	1189	0	0	0	0	0
AIR FLOW (TOTAL)		KP/Hr	1037	2521	2405	2750	2732	2490
FEED WATER FLOW		KP/Hr	3036	1970	1937	1927	2007	1985
STEAM FLOWS	MAIN STEAM	KP/Hr	9083	2055	2040	2040	2049	2049
	REHEAT STM	KP/Hr	–	FOUND FROM HEAT BALANCE				–
	AUX STEAM	KP/Hr	4000	24	25	25	25	25
	SAH EXTR	KP/Hr	4017	16	11	23	23	23
	SAH AUX	KP/Hr	4018	12	0	0	11	13
	AUX TO S.T.A.E.	KP/Hr	?	~	~	~	~	~
CONDENSATE FLOW		KP/Hr	3017	1766	1656	1766	1915	1686
DE SUPER-HEATER SPRAY FLOWS	SH LEFT	KP/Hr	3042	54	61	56	31	32
	SH RIGHT	KP/Hr	3043	36	32	38	22	20
	REHEAT	KP/Hr	3044	0	0	0	0	0
BLOW DOWN FLOW		KP/Hr	CR	–	–	–	–	–

UP&L HUNTER #2 OPERATING DATA (PG 3 OF 8)

TEST NUMBER	60	61	62	63	64
DATE	8-18-81	8-18-81	8-18-81	8-18-81	8-18-81
TIME (MILITARY)	00:20	01:58	04:05	04:44	5:50

DAMPER SETTINGS

OVER FIRE AIR (OFA) TOP	PERCENT OF FULL OPEN	READ IN CONTROL ROOM	0	0	0	60	40
OVER FIRE AIR (OFA) BOT			0	0	0	60	40
AUX AIR 0-1 (TOP)			0	0	8	0	0
FUEL AIR #1			100	100	100	100	100
AUX AIR 1-2			0	0	8	0	0
FUEL AIR #2			100	100	100	100	100
AUX AIR 2-3			0	0	8	0	0
FUEL AIR #3			100	100	100	100	100
AUX AIR 3-4			0	0	8	0	0
FUEL AIR #4			100	100	99	98	97
AUX AIR 4-5			0	0	8	0	0
FUEL AIR #5			25	25	25	25	25
AUX AIR 5-6		LOCAL	60	60	60	0	0
FAN DAMPERS FD 1 IN		CONTROL ROOM	59	56	61	61	58
FAN DAMPERS FD 1 OUT			100	100	100	100	100
FAN DAMPERS FD 2 IN			60	58	63	62	59
FAN DAMPERS FD 2 OUT			100	100	100	100	100
FAN DAMPERS ID 1 IN			66	68	71	67	66
FAN DAMPERS ID 1 OUT			100	100	100	100	100
FAN DAMPERS ID 2 IN			63	63	67	63	63
FAN DAMPERS ID 2 OUT			100	100	100	100	100

VALVE POSITIONS

DE SUPER-HEAT SPRAY VALVES SH L	% OPEN	CR	32	33	34	24	23
DE SUPER-HEAT SPRAY VALVES SH R	% OPEN	CR	38	38	40	31	30
DE SUPER-HEAT SPRAY VALVES RH	% OPEN	CR	0	0	0	0	0

TILTS (LOG 73)

OVER FIRE AIR (OFA)	DEG UP	LOCAL	0	0	0	0	0
BURNER TILTS LR	DEG UP	1181	-1 [illegible]	-1 [illegible]	-1 (MAN)	-1 (MAN)	-1 (MAN)
BURNER TILTS LF	DEG UP	1182	-1	-1	-1	-1	-1
BURNER TILTS RF	DEG UP	1183	0	0	0	0	0
BURNER TILTS RR	DEG UP	1184	-2	-2	-2	-2	-2

UP&L HUNTER #2 OPERATING DATA

PG 4 OF 8

TEST NUMBER	60	61	62	63	64
DATE	8-18-81	8-18-81	8-18-81	8-18-81	8-18-81
TIME (MILITARY)	00:25	02:00	04:18	04:45	05:52

PRESSURES (STEAM & WATER) (LOG 74)

FEED WATER TO ECONZR		P.S.I.G.	NA	~	~	~	~	~
BOILER DRUM PRES			1161	2557	2545	2538	2542	2545
THROTTLE STEAM			2000	2413	2401	2397	2397	2402
TURBN 1ST STAGE			2023	1238	1230	1228	1228	1232
REHEAT INLET (COLD)	LEFT		NA	~	~	~	~	~
	RIGHT		NA	~	~	~	~	~
	AVG		NA	~	~	~	~	~
TURB COLD REHEAT			2106	402	399	398	396	397
HOT REHEAT @ BOILER			1043	373	370	369	367	368
HP FW HTR #7 (EXTR STM)			2040	398	395	394	392	393
MAIN STM @ BOILER			1153	2410	2400	2393	2394	2400
AUX STEAM PRES			4125	339	340	338	341	340

PRESSURES (AIR & GAS) (LOG 74)

FD FAN OUTLETS	#1	INCHES OF WATER (GUAGE) - In W (G)	CR	7.0	5.9	8.5	7.6	6.5
	#2		CR	8.9	7.4	10.0	8.4	7.9
	AVG		NA	~	~	~	~	~
AIR HEATERS ΔP (AIR)	#1		1000	1.7	1.6	2.0	2.0	1.6
	#2		1001	2.2	2.0	2.5	2.5	2.2
	AVG		NA	~	~	~	~	~
WINDBOX	L		CR	3.5	2.8	4.2	3.4	2.8
	R		CR	3.6	2.8	4.2	3.6	3.0
	AVG		NA	~	~	~	~	~
WINDBOX/FURNACE: ΔP	L		CALCULATED IN CONTROL ROOM	3.8	3.1	4.9	3.7	3.4
	R			4.1	3.4	5.[illegible]	4.2	3.8
FURNACE PRESSURE			1163	-0.5	-0.75	-0.6	-0.4	-0.4
SH GAS ΔP			1034	1.2	1.1	1.4	1.3	1.1
ECONMZR GAS ΔP			1027	1.8	1.7	2.1	2.0	1.7
GAS AT AIR HEATER OUTLET	#1		CR	7.6	6.7	8.6	8.4	7.6
	#2		CR	8.2	7.4	9.1	8.8	8.3
	AVG		NA	~	~	~	~	~
ID FAN INLET PRESSURE	#1		1019	-9.2	-9.	-10.6	-10.	-9.1
	#2		1023	-9.7	-9.4	-10.8	-11.	-9.5
	AVG		NA	~	~	~	~	~
ATMOSPHERIC BAROM		In Hg (A)	4122	24.49	24.49	24.49	24.49	24.51
MILL PRESSURES		→		SEE	MILL	DATA	SHEET	←

UP&L HUNTER #2 OPERATING DATA

PG 5 OF 8

TEST NUMBER	60	61	62	63	64
DATE	8-18-81	8-18-81	8-18-81	8-18-81	8-18-81
TIME (MILITARY)	00:27	02:01	04:08	04:47	5:53

TEMPERATURES (AIR & GAS) (LOGS 74 & 75)

LOG 75 | LOG 74

AMBIENT AIR TEMP		DEGREES FARENHEIT - (°F)	4035	69	65	63	64	63
FD FAN OUTLET	#1		1014	81	80	76	76	73
	#2		1015	79	79	75	74	73
STEAM AIR HTR OUTLET	#1		1002	105	105	108	105	107
	#2		1004	106	111	106	102	105
AIR HEATER AIR TEMPS	IN #1		1016	105	104	105	102	105
	IN #2		1017	107	115	103	101	101
	OUT (AVG) #1		1003	490	478	475	474	474
	OUT (AVG) #2		1005	487	483	487	486	483
AIR HEATER GAS TEMPS	IN #1		1010	588	577	589	586	578
	IN #2		1012	602	591	604	602	594
	OUT (AVG) #1		1018	250	249	248	250	247
	OUT (AVG) #2		1022	254	256	255	259	256
COAL AIR MILL OUTLET TEMPS	#1		1053	162	161	162	162	161
	#2		1054	165	164	164	163	163
	#3		1055	165	164	164	163	163
	#4		1056	165	164	163	162	162
	#5		1057	128	114	104	102	98

TEMPERATURES (STEAM & WATER) (LOC 75)

(SAME AS HP HTR #7 FW OUT)

FW TO ECONMZR		DEGREES FARENHEIT - (°F)	3037	456	456	455	454	454
ECONMZR OUT (AVG)			NA	∼	∼	∼	∼	∼
BOILER DOWNCOMER			6039	649	648	647	646	647
MAIN STEAM DE-SUPER-HEATER	IN L		1048	752	743	754	748	742
	IN R		1049	757	753	759	746	742
	OUT L		1050	718	712	718	725	721
	OUT R		1051	726	720	725	732	728
THROTTLE STEAM			2001	1006	1014	1007	1001	1002
REHEAT	COLD OUT OF TURBINE D/S		2109	595	601	597	589	590
	COLD L		1045	596	601	596	589	590
	COLD R		1046	591	596	591	585	586
	HOT @ BOILER		1044	999	1001	990	970	972
HIGH PRES FEED WATER HTR #7	EXTR STEAM (STEAM IN)		2041	595	599	594	588	589
	FW IN		3030	387	387	387	385	386
	DRAIN		3029	394	393	393	392	392
AUX. STEAM			4001	603	606	606	611	611

UP&L HUNTER #2 OPERATING DATA

PG 6
OF 8

	60	61	62	63	64
TEST NUMBER	60	61	62	63	64
DATE	8-18-81	8-18-81	8-18-81	8-18-81	8-18-81
TIME (MILITARY)	00:27	02:02	04:08	04:47	5:54

MILL DATA (LOG 76)

MILL AMPERES	#1	AMPERES	1148	71	70	70	71	69
	#2		1149	68	66	69	69	67
	#3		1150	70	68	69	70	67
	#4		1151	69	69	68	68	68
	#5		1152	0	0	0	0	0
COAL AIR TEMPS		—→		SEE "TEMPERATURE" DATA SHEET				
EXHAUSTER DISCHARGE PRESSURE	#1	IN W(G)	CR	8.5	8	8.0	8	8
	#2		CR	65	6.5	6.5	6.5	6
	#3		CR	7.5	7	7.5	7	7.5
	#4		CR	7.5	7.5	7.5	7.5	7.5
	#5		CR	0	0	0	0	0
MILL BOWL ΔP	#1	In W(g)	CR	7	7	7	7	7
	#2	In W(g)	CR	7	7	7	7	7
	#3	In W(g)	CR	7	7	7	7	7
	#4	In W(g)	CR	7	7	7	7	7
	#5	In W(g)	CR	0	0	0	0	0
SUCTION	#1	IN W(G)	CR	2.0	2.0	1.9	2.0	2.0
	#2		CR	2.0	2.1	2.1	2.2	2.3
	#3		CR	1.9	1.9	1.8	1.8	2.0
	#4		CR	1.9	1.9	2.0	2.1	2.1
	#5		CR	1.1	1.0	0.9	1.0	1.0
FEEDER SPEED (COAL)	#1	% OF FULL	CR	66	66	65	64	64
	#2		CR	66	66	64	64	64
	#3		CR	66	66	64	64	64
	#4		CR	65	66	65	64	64
	#5		CR	0	0	0	0	0

UP&L HUNTER #2 OPERATING DATA

PG 7 OF 8

TEST NUMBER	60	61	62	63	64
DATE	8-18-81	8-18-81	8-18-81	8-18-81	8-18-81
TIME (MILITARY)	00:24	02:03	04:10	04:48	05:54

EMISSIONS & ENVIRONMENTAL DATA (LOG 76)

AMBIENT OUTSIDE AIR	TEMPERATURE	°F	4035	60	65	63	63	63
	RELTIV HUMIDITY	%	UNIT 1 GROUP 37	BAD	BAD	BAD	BAD	BAD
	BAROM. PRES.	IN Hg (G)	4122	24.49	24.49	24.49	24.49	24.51
	WIND SPEED	MPH	UNIT 2 GROUP 37 (OR CR)	0	1	1	4	0
	WIND DIRECTION	–		WNW	SSE	N	N	S[illegible]
O2 @ AH INLET	RIGHT	%	1029	4.65	3.73	5.83	6.08	5.03
	LEFT	%	1031	3.89	2.95	4.93	4.88	3.90
	AVG	%	9007	4.23	3.34	5.43	5.46	4.46
SO2	ENTERING SCRUB'R	PPm	SCRBR	~~~	~~~	~~~	~~~	~~~
SO2 IN STACK	INSTANTANEOUS	PPM	1032	205	211	209	210	209
		#/MBtu	NA	~~~	~~~	~~~	~~~	~~~
	LAST 3 Hr AVG	#/MBtu	CR	0.438	0.453	0.471	0.471	0.492
NOx IN STACK	INSTANTANEOUS	PPM	1033	218	172	244	177	158
		#/MBtu	NA	~~~	~~~	~~~	~~~	~~~
	LAST 3 Hr AVG	#/MBtu	CR	0.360	0.331	0.325	0.325	0.365
CO2 IN STACK		%	1166	12.61	13.29	11.70	11.60	12.6
STACK SMOKE OPACITY	NOW OBSERVER	%	PSN	—	—	—	—	—
	NOW INSTRUMENT	%	1052	12.4	11	15	14	12.2
	LAST HOUR AVG	%	1052H	11.9	11	14	14	13.5

MISCELANEOUS DATA (LOG 76)

DRUM LEVEL	IN W(G)	1038	0.34	0.16	−0.04	−0.35	−0.1
FAN AMPRES FD #1	Amps	1073	114	110	117	115	112
FAN AMPRES FD #2	Amps	1074	118	112	121	119	114
FAN AMPRES ID #1	Amps	1083	247	242	252	248	246
FAN AMPRES ID #2	Amps	1084	249	245	252	249	248
SCRUBBER ON?	Y or N	—	Y?	Y?	Y?	Y?	Y?
SLAG BLOWING?	Y or N	CR	N	N	N	N	N
SOOT BLOWING?	Y or N	CR	N	Y (SH)	N	N	N
OIL IGNITORS ON?	Y or N	CR	N	N	N	N	N

UP&L HUNTER #2 OPERATING DATA

PAGE 8 OF 8

TEST NUMBER	60	61	62	63	64
DATE	8-18-81	8-18-81	8-18-81	8-18-81	8-18-81
TIME (MILITARY)	00:22	01:56	04:18	4:40	5:40

NOTES & COMMENTS

	60	61	62	63	64
	MILL #5 IS STILL LIMITTED BY A VIBRATION PROBLEM TO ~65 % (MAX) OF FULL CAPACITY.	MILL #5 IS STILL LIMITTED TO ~65 % OF FULL CAPACITY. CONTROL ROOM'S XS AIR CONTROL IS SET TO -1.0	MILL #5 IS STILL LIMITTED TO ~65% OF FULL CAPACITY. PLANTS XS AIR CONTROL IS AT +1.0.		

APPENDIX II

FLUE GAS DATA (SAMPLE COMPUTER REPORT)

Due to the large volume of flue gas data, it is impractical to present all of it here. However, the data have already been summarized in Parts C and D of this report. The purpose of this appendix is to present an example of the detail upon which the summaries are based.

During each period of flue gas analyses (typically 20-30 minutes), gas was sampled, in turn, from four probe assemblies in the economizer outlet (each probe assembly being a composite of three probe samples, as described in Section I of Part B of this report). While the each test was in progress, a computer CRT display showed the following information for each of the four samples (in real time):

- instantaneous values (NO_x, CO, O_2 and CO_2)
- running average
- running average corrected to standard dilution (3% O_2, dry)

At the conclusion of each test, a hard copy was printed which summarized the results of the test. The hard copy (example on next page) reported the average measured values of all gases for each probe on an individual basis as well as the corrected averages. The report also included averages for probes 1 and 2, which shared the west duct, and probes 3 and 4 which shared the east duct.

```
                        STATION : UP&L HUNTER
                           UNIT # : 2
                        DATE : 08/18/81 06:16:08
                           TEST # : 64

     TITLE : UP&L TEST #64 MEDIUM LOAD NORMAL XS AIR TEST OFA OPEN 60%


AVERAGED VALUES AS MEASURED (DRY)

PROBE    O2      NOX      NO        NO       NO2     CO      CO2     SO2     HC
  #                     (CHEMI)   (NDIR)
       (PCNT)   (PPM)    (PPM)     (PPM)    (PPM)   (PPM)   (PCT)   (PPM)   (PPM)
       (MEAS)

  1     5.91    341.     351.       0.       0.      11.    12.56    0.      0.
  2     5.72    344.     354.       0.       0.      10.    13.09    0.      0.
  3     5.26    351.     358.       0.       0.      10.    13.47    0.      0.
  4     4.99    356.     359.       0.       0.      11.    13.79    0.      0.
1 & 2   5.81    342.     352.       0.       0.      10.    12.82    0.      0.
3 & 4   5.13    353.     359.       0.       0.      11.    13.63    0.      0.
 ALL    5.47    348.     356.       0.       0.      11.    13.23    0.      0.


AVERAGED VALUES CORRECTED TO 3% OXYGEN

PROBE    O2      NOX      NO        NO       NO2     CO      CO2     SO2     HC
  #                     (CHEMI)   (NDIR)
       (PCNT)   (PPM)    (PPM)     (PPM)    (PPM)   (PPM)   (PCT)   (PPM)   (PPM)
       (MEAS)

  1     5.91    403.     421.       0.       0.      13.    14.99    0.      0.
  2     5.72    403.     420.       0.       0.      11.    15.42    0.      0.
  3     5.27    402.     409.       0.       0.      11.    15.41    0.      0.
  4     4.98    399.     404.       0.       0.      13.    15.49    0.      0.
1 & 2   5.82    403.     420.       0.       0.      12.    15.20    0.      0.
3 & 4   5.13    401.     407.       0.       0.      12.    15.45    0.      0.
 ALL    5.47    402.     414.       0.       0.      12.    15.33    0.      0.

   0.550  POUNDS NOX PER MILLION BTU USING F SUB D TECHNIQUE
   0.573  POUNDS NOX PER MILLION BTU (F SUB C)

TOTAL SAMPLING TIME FOR PROBE #1 =    4.0 MINUTES
TOTAL SAMPLING TIME FOR PROBE #2 =    4.0 MINUTES
TOTAL SAMPLING TIME FOR PROBE #3 =    4.0 MINUTES
TOTAL SAMPLING TIME FOR PROBE #4 =    4.0 MINUTES

CONCENTRATIONS OF GASES USED FOR CALIBRATION :
   O2     (LO)--CO--(HI)      NO       NO2      CO2      CH4      SO2
  PCNT      PPM       PPM     PPM      PPM      PCNT     PPM      PPM
  4.00     131.0      0.0    468.0     0.0      13.3     0.0      0.0

 SAMPLING TEAM : MJR PSN RFL RC
 NOTES : SIMILAR TO TEST #57 EXCEPT TOP MILL NOW ON AND BOTTOM MILL OFF
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APPENDIX III

CONVERSION FACTORS, F FACTORS, AND SAMPLE CALCULATIONS

$$* \quad \boxed{\left(\begin{array}{c}\text{Concentration Corrected to}\\ \text{X\% } O_2 \text{ Dilution}\end{array}\right) = \left(\begin{array}{c}\text{Actually Measured}\\ \text{Concentration at}\\ \text{Actual } O_2\\ \text{Dilution (Y\% } O_2\text{)}\end{array}\right) \cdot \left(\frac{21 - X}{21 - Y}\right)}$$

Example: 400 ppm NO_x at 4% O_2 = 423.5 ppm at 3% O_2.

$$* \quad \boxed{\left(\begin{array}{c}\text{Flow Rate}\\ \text{Corrected to X\% } O_2\end{array}\right) = \left(\begin{array}{c}\text{Flow Rate At}\\ \text{Y\% } O_2\end{array}\right) \cdot \left(\frac{21 - Y}{21 - X}\right)}$$

Example: A gas having flow rate 10 ft^3/min at 4% O_2 would have flow rate 9.444 at 3% O_2. (Assuming all other conditions -- % moisture, temp, press -- remain unchanged.)

$$\boxed{\left(\begin{array}{c}\text{Concentration}\\ \text{on Dry Basis}\end{array}\right) = \left(\begin{array}{c}\text{Concentration}\\ \text{on Wet Basis}\end{array}\right)\left(\frac{1}{1 - \text{(fraction of moisture)}}\right)}$$

Example: If SO_2 has concentration 2.00μg/WSCF** in a gas containing 10% H_2O vapor by volume, then its concentration on a dry basis would be:

---

* These formulas assume that oxygen can enter or leave the system only in the form of air. That is: every volume of O_2 crossing the system boundary is accompanied by 3.76 volumes of inert gas. (Air is 21% O_2.)

** WSCF = Wet Standard Cubic Foot (68°F, 1 Atm).

$$\begin{pmatrix}\text{Concentration}\\ \text{on Dry Basis}\end{pmatrix} = \left(2.0\ \frac{\mu g}{ft^3}\right)\left(\frac{1}{1-0.10}\right) = 2.22\ \mu g/DSCF$$

$$\boxed{\text{ppm} = \left(\frac{\begin{pmatrix}\text{Concentration by weight } (g/m^3)\\ \text{at temperature T (K)}\\ \text{and pressure P (Atm)}\end{pmatrix}}{\begin{pmatrix}\text{molecular}\\ \text{weight}\end{pmatrix}: \text{ g/gMole}}\right)\left(82.05^*\right)\left(\frac{T\ (^0K)}{P\ (Atm)}\right)}$$

Example: Suppose SO_3 (molecular weight = 80 g/gMole) has a concentration (by weight) of 300 mg/DSCM.** What is its concentration in parts per million?

$$\text{ppm} = \left(\frac{0.300}{80}\right)(82.05)\left(\frac{293}{1}\right) = 90.15 \text{ ppm, Dry}$$

Because the original concentration was given on a dry basis, the converted result is also still on a dry basis.

Of course, the above equation may be rearranged to facilitate conversion from ppm to grams/meter^3 at any temperature and pressure.

$$\begin{pmatrix}\text{Concentration by weight } (g/m^3)\\ \text{At Temperature T...}(^0K)\\ \text{and Pressure P.....(Atm)}\end{pmatrix} = \frac{(\text{ppm})\begin{pmatrix}\text{Molecular wt}\\ \text{of specie}\\ \text{of interest}\\ \text{(g/gMole)}\end{pmatrix}(P(\text{Atm}))}{(82.05)(T(K))}$$

(The reader should note that this is valid for ordinarily encountered concentrations where the volume percent of the pollutant is small. That is: < ~ 10,000 ppm)

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*82.05 is the value of "R," the universal ideal gas constant, and has units of $\frac{cm^3 \cdot Atm}{gMole \cdot K}$

**DSCM = Dry standard cubic meter (T = 293K, P = 1 atm.)

"F" FACTOR METHOD FOR CONVERTING TO THE STANDARD UNIT OF EMISSION; POUNDS/MBtu

The "F" factor method can be used to convert the emission rate to the standard units of pounds per MBtu through of the following equation:*

$$\boxed{\left(\frac{\text{Pounds}}{\text{MBtu}}\right) = \left(\frac{\text{Pounds}}{\text{DSCF}}\right)^{**} \quad (F_d) \left(\frac{21}{21 - \%O_2}\right)}$$

Where $\%O_2$ = Oxygen concentration at which the value marked by the double asterisk is valid.

F_d = The "F" factor for the fuel being burned. It has units of DSCF/MBtu. (at 0% O_2, dry basis)

For bituminous coal, the EPA-APTI training manual* gives:

$$F_d = 9820 \ \frac{\text{DSCF}}{\text{MBtu}} \ (\text{at } 0\% \ O_2)$$

This assumes complete combustion, and no excess oxygen - an assumption already factored into the previous equation.

---

*G. J. Aldina, J. A. Jahnke, "Source Sampling for Particulate Pollutants" pg. 140, manual for course No. 450 of EPA's Air Pollution Training Institute. Prepared by Northrup Services Inc., under EPA contract No. 68-02-2374, January 1978.

**Obtained by conversion of the formula for "concentration by weight" listed on the preceding page.

As an alternative, EPA allows F_d to be calculated from fuel analysis according to the following formula (given on pg 145 of the above referenced manual):

$$F_d = \frac{10^6\ (3.64\ \%H + 1.53\ \%C + 0.57\ \%S + 0.14\ \%N - 0.46\ \%O)}{\text{High Heating Value: Btu/lb}}$$

In this report, the tabulated value (9820) was used.

The next few pages contain summaries of import conversion factors in both English and metric units.

CONVERSION FACTORS
SI Units to Metric Units or English Units

To Obtain	From	Multiply By
g/Mcal	ng/J	0.004186
10^6 Btu	GJ	0.948
MBH/ft^2	GJ·hr^{-1}m^{-2}	0.08806
MBH**/ft^3	GJ·hr^{-1}·m^{-3}	0.02684
Btu	gm cal	3.9685×10^{-3}
10^3 lb/hr* or MBH	GJ/hr	0.948
10^3 lb/hr* or MBH	MW$_{th}$	3.413
lb/MBtu	ng/J	0.00233
ft	m	3.281
in	cm	0.3937
mils	cm	393.7
ft^2	m^2	10.764
ft^3	m^3	35.314
lb	Kg	2.205
°Rankin	°Kelvin	1.80
°Fahreinheit	°Celsius	$t_F = 9/5(t_c)+32$
°Fahrenheit	°Kelvin	$t_F = 1.8\ T_k - 460$
°Rankin	°Fahrenheit	$t_R = t_F + 460$
psig	Pa	$P_{psig} = (P_{pa})(0.0001450)-14.7$
psia	Pa	$P_{psia} = (P_{pa})(0.0001450)$
iwg*** (39.2°F)	Pa	$P_{iwg} = (P_{pa})(0.004014)$
in Hg	Pa	0.000295
in Hg	in H$_2$O	1/13.6
in Hg	atm	760
in Hg	mm Hg	1/25.4
in Hg	psi	2.036

To Obtain ppm (dry) at 3% O$_2$ for	Multiply Flow Concentrations in ng/J, by
Natural Gas Fuel	
CO	3.23
HC	5.65
NO$_x$, NO, or NO$_2$ (As Equivalent NO$_2$)	1.96
SO$_x$ (SO$_2$)	1.41
Oil Fuel	
CO	2.93
HC	5.13
NO$_x$, NO, or NO$_2$ (As Equivalent NO$_2$)	1.78
SO$_x$ (SO$_2$)	1.28
Coal Fuel	
CO	2.69
HC	4.69
NO	2.52
NO$_x$, NO or NO$_2$ (As Equivalent NO$_2$)	1.71
SO$_x$ (SO$_2$)	1.18

---

*lb/hr of equivalent saturated steam. (For water, the heat of the liquid-gas phase change is about 10^3 Btu/pound.)

**10^6 Btu/hr

***The symbols iwg and in H$_2$O g are used interchangeably in this report to indicate gauge pressure in inches of water.

CONVERSION FACTORS
ENGLISH AND METRIC UNITS TO SI UNITS

To Obtain	From	Multiply By
ng/J	lb/MBtu	430
ng/J	g/MCal	239
GJ hr^{-1} m^{-2}	MBH**/ft^2	11.356
GJ hr^{-1} m^{-3}	MBH/ft^3	37.257
GJ/hr	10^3 lb/hr* or MBH	1.055
MW_{th}	10^3 lb/hr* or MBH	0.293
m	ft	0.3048
cm	in	2.54
cm	mils	0.00254
m^2	ft^2	0.0929
m^3	ft^3	0.02832
Kg	lb	0.4536
°Kelvin	°Rankin	5/9
°Celsius	°Fahrenheit	$t_c = (5/9)(t_F-32)$
°Kelvin	°Fahrenheit	$t_k = ((5/9)(t_F-32)) + 273$
°Kelvin	°Celsius	$t_k = t_c + 273$
Pa	psig	$P_{pa} = (P_{psig} + 14.7)(6895)$
Pa	psia	$P_{pa} = (P_{psia})(6895)$
Pa	iwg*** (39.2°F)	$P_{pa} = (P_{iwg})(249.1)$
Pa	in Hg	3385
in H_2O	in Hg	13.6
atm	in Hg	1/760
mmHg	in Hg	25.4
psi	in Hg	0.491

To Obtain ng/J for:	Multiply Concentrations (in ppm dry at 3% O_2) by
Natural Gas Fuel	
CO	0.310
HC	0.177
NO_x, NO, or NO_2 (As Equivalent NO_2)	0.510
SO_x (SO_2)	0.709
Oil Fuel	
CO	0.341
HC	0.195
NO_x, NO, or NO_2 (As Equivalent NO_2)	0.561
SO_x (SO_2)	0.780
Coal Fuel	
CO	0.372
HC	0.213
NO	0.395
NO_x, NO, or NO_2 (As Equivalent NO_2)	0.589
SO_x (SO_2)	0.850

---

*lb/hr of equivalent saturated steam. (For water, the heat of the liquid-gas phase change is about 10^3 Btu/pound.)

**10^6 Btu/hr

***The symbols iwg and in H_2O g are used interchangeably in this report to indicate gauge pressure in inches of water.

CONVERSION FACTORS
ENGLISH TO SI UNITS

To Convert From	To	Multiply By*
Btu	Gigajoule, GJ	1.055 056 E-06
MBtu/h	Megawatt, MW$_{th}$	2.93 E-01
Btu/lb	Gigajoule/kilogram, GJ/kg	2.326 000 E-06
Btu/lb	Calories/gram, cal/g	5.559 273 E-01
Pounds/square inch	Megapascal, MPa	6.894 757 E-03
	Kilopascal, kPa	6.894 757 E+00
Pounds hour, lb/h	Kilogram/hour, kg/h	4.535 934 E-01
Pounds/hour, lb/h	Metric tons/hour, t/h	4.535 925 E-04
Tons (short)	Metric tons, t	9.071 847 E-01
Pounds, lb	Kilogram, kg	4.535 924 E-01
Feet, ft	Meter, m	3.048 000 E-01
Square Feet, ft^2	Meters^2, m^2	9.290 304 E-02
Inches, in.	Centimeters, cm	2.540 000 E-00
Inches, in.	Meter, m	2.540 000 E-02
Grains/cubic foot	Milligrams/meter^3, mg/m^3	2.288 351 E-01
Cubic feet, ft^3	Meter^3, m^3	2.831 685 E-02
	Decimeter^3, dm^3	2.831 685 E+01
Gallons	Meters^3, m^3	3.785 412 E-03
	Decimeter^3, dm^3	3.785 412 E+00

* Numbers expressed in power-of-ten notation using E + xx to indicate the power of ten. For example:

$$1.055\ 056 \text{ E-06} = 1.055\ 056 \times 10^{-6} = .000001055056$$

CONVERSION FACTORS FOR NO_x EMISSIONS ROM BITUMINOUS COAL COMBUSTION

To Convert From	To	For NO_x* Emissions (as NO_2) Multiply By
ppm at 3% O_2 Dry	$\frac{g}{DSCM}$ at 3% O_2	0.0019134
$\frac{g}{DSCM}$ at 3% O_2	$\frac{g}{DSCM}$ at 0% O_2	1.167
$\frac{g}{DSCM}$ at 0% O_2	$\frac{g}{DSCF}$ at 0% O_2	0.02832
$\frac{g}{DSCF}$ at 0% O_2	$\frac{g}{MBtu}$	9,820
$\frac{g}{MBtu}$	$\frac{lb}{MBtu}$	0.002205
$\frac{lb}{MBtu}$	$\frac{ng}{J}$	430

ppm at 3% O_2 (dry)	lb/MBtu	0.001367
ppm at 3% O_2 (dry)	ng/J	0.5878

---

* In these calculations, consistent with EPA guidelines, NO_x is treated as 100% NO_2 (molecular weight = 46 lb/lbMole) since it is felt that all NO_x is eventually converted in the atmosphere to NO_2. Actual flue gas measurements, however, indicate that NO_x has a composition of $\leq$ 5% NO_2 and 95% NO (MW = 30.8).

STANDARD CONDITIONS

EPA defines standard temperature and pressure (STP) as 20°C and 1 atm.

- 20°C = 293°K = 68°F = 528°R
- 1 atm = 760 mmHg = 29.92 in Hg = 14.7 psia = 406.8 in H_2O = 101.3 kPa

INCHES TO MILS

one inch = 1,000 mils
one mil = 0.001 inch

VOLUME ABBREVIATIONS*

m^3 = Cubic meters
SCM = Standard cubic meters
ACM = Actual cubic meters
WSCM = Standard cubic meters (wet basis)
DSCM = Standard cubic meters (dry basis)

ft^3 = Cubic feet
SCF = Standard cubic feet
ACF = Actual cubic feet
WSCF = Standard cubic feet (wet basis)
DSCF = Standard cubic feet (dry basis)

* For additional abbreviations, see the table of abbreviations and symbols at the beginning of this report.

APPENDIX IV

PORTIONS OF METHOD 17 AND PSD REPORTS

EPA Method 17 (similar to Method 5 except for the filter location) was used to measure particulate loading in the flue gas as explained in Section II of Part B of this report. Similarly, the size distribution of those particles was measured by a cascading inertial impactor method. The following pages contain selected samples of data and test results from the report by from Entropy Environmentalists', Inc. Method 17 testing was done at the inlet to the electrostatic precipitator (ESP), as well as at the ESP outlet (simultaneously). Three such pairs of inlet/outlet tests (No. 1/No. 4; No. 2/No. 5; and No. 3/No. 6) were performed, thus allowing three evaluations of precipitator efficiency. Similarly three particle size distribution (PSD) tests No (S1, S2, and S3) were performed at ESP inlet. Example data is presented in the following pages.

SUMMARY OF RESULTS

TABLE 1

PARTICULATE CONCENTRATIONS & PRECIPITATOR EFFICIENCIES

Simultaneous Runs	Concentrations, Gr/DSCF Inlet	Outlet	Collection Efficiency, %
1, 4	3.281	0.0130	99.6
2, 5	3.526	0.0081	99.8
3, 6	3.714	0.0289	99.2
Average	3.507	0.0167	99.5

TABLE 2

INLETS PARTICLE SIZING TESTS SUMMATION

-- ~~B~~A-Side Inlet Run S1 --

AERODYNAMIC DIA.-MICRONS	CUMULATIVE % LESS THAN DIA.
14.81	24.4
9.23	21.7
6.24	19.8
4.24	18.2
2.70	14.0
1.34	10.8
0.81	10.4
0.60	10.4

-- ~~A~~B-Side Inlet Run S2 --

AERODYNAMIC DIA.-MICRONS	CUMULATIVE % LESS THAN DIA.
14.08	21.6
8.77	16.8
5.93	12.5
4.03	9.8
2.56	7.6
1.26	5.6
0.76	5.0
0.56	5.0

-- ~~A~~B-Side Inlet Run S3 --

AERODYNAMIC DIA.-MICRONS	CUMULATIVE % LESS THAN DIA.
14.84	22.6
9.25	17.3
6.26	10.6
4.25	7.0
2.71	2.9
1.34	1.0
0.81	0.30
0.60	0.20

TABLE 3

PARTICULATE TESTS SUMMARY OF RESULTS

Unit #2 Precipitator Inlet

	1	2	3
RUN DATE	10/13/82	10/13/82	10/14/82
TEST TRAIN PARAMETERS:			
VOLUME OF DRY GAS SAMPLED, SCF*	82.539	84.023	74.031
PERCENT ISOKINETIC	103.4	106.1	102.1
STACK PARAMETERS:			
TEMPERATURE, DEG. F	247	254	248
AIR FLOW RATES SCFM*, DRY	1,045,630	1,036,933	949,211
ACFM, WET	1,877,639	1,891,417	1,720,708
METHOD 17 TEST RESULTS:			
CATCH, MILLIGRAMS	17,549.2	19,198.8	17,818.4
GRAINS PER DSCF*	3.2812	3.5262	3.7144
LBS PER HOUR	29,407.66	31,340.88	30,220.75

* 68 Deg. F. - 29.92 in. Hg.

TABLE 4

PARTICULATE TESTS SUMMARY OF RESULTS

Unit #2 Precipitator Outlet

	4	5	6
RUN DATE	10/13/82	10/13/82	10/14/82
TEST TRAIN PARAMETERS:			
VOLUME OF DRY GAS SAMPLED, SCF*	103.249	101.215	94.732
PERCENT ISOKINETIC	107.3	105.0	104.4
STACK PARAMETERS:			
TEMPERATURE, DEG. F	241	251	239
AIR FLOW RATES SCFM*, DRY	892,062	879,540	841,072
ACFM, WET	1,609,350	1,616,963	1,517,144
PERCENT EXCESS AIR	34.3	26.4	28.7
HEAT INPUT, MBTU/HR	4,032.6	4,234.1	3,974.9
METHOD 17 TEST RESULTS:			
CATCH, MILLIGRAMS	86.8	53.0	177.1
GRAINS PER DSCF*	0.0130	0.0081	0.0289
LBS PER HOUR	99.20	60.92	207.99
LBS PER MILLION BTU	0.0246	0.0144	0.0523

* 68 Deg. F. - 29.92 in. Hg.

TABLE 5

EMISSIONS & EFFICIENCIES, A-SIDE & B-SIDE*

B ~~A~~-Side

Run No.	Concentration, Gr/DSCF Inlet	Concentration, Gr/DSCF Outlet	Eff.(%)	Emissions, Lb/Hr Inlet	Emissions, Lb/Hr Outlet
1 & 4	3.414	0.00855	99.7	15,875	33.97
2 & 5	3.473	0.00478	99.9	15,903	18.79
3 & 6	4.063	0.0371	99.1	17,261	142.17
Average	3.650	0.0168	99.6	16,346	65.0

A ~~B~~-Side

Run No.	Concentration, Gr/DSCF Inlet	Concentration, Gr/DSCF Outlet	Eff.(%)	Emissions, Lb/Hr Inlet	Emissions, Lb/Hr Outlet
1 & 4	3.141	0.0178	99.4	13,543	65.48
2 & 5	3.576	0.0116	99.7	15,405	42.00
3 & 6	3.342	0.0194	99.4	12,948	65.22
Average	3.353	0.0163	99.5	13,965	57.57

---

* Based upon particulate catches from half of the run performed on the A-side or B-side.

PROCESS DESCRIPTION AND OPERATION

Utah Power and Light Company's Hunter Generating Station in Castledale, Utah uses coal-fired boilers for the production of steam necessary to drive turbines for the generation of electricity.

In general, the bituminous coal is first pulverized and then blown into the combustion chamber with exhauster fans. This provides simultaneous fuel suspension and fuel combustion. Potential emissions include the products of complete and incomplete combustion, along with any extraneous material in the coal.

As shown in Figure 1, the flue gases leave the boiler and pass through an economizer, two air heaters, and four mechanical collectors before entering the electrostatic precipitator. Gases off the precipitator are ducted to the scrubber by two induced draft fans and drawn to the stack by two more fans before exhausting to the atmosphere.

During the testing, Unit #2 was producing 375 megawatts for the first two set of runs and 350 megawatts for the third set.

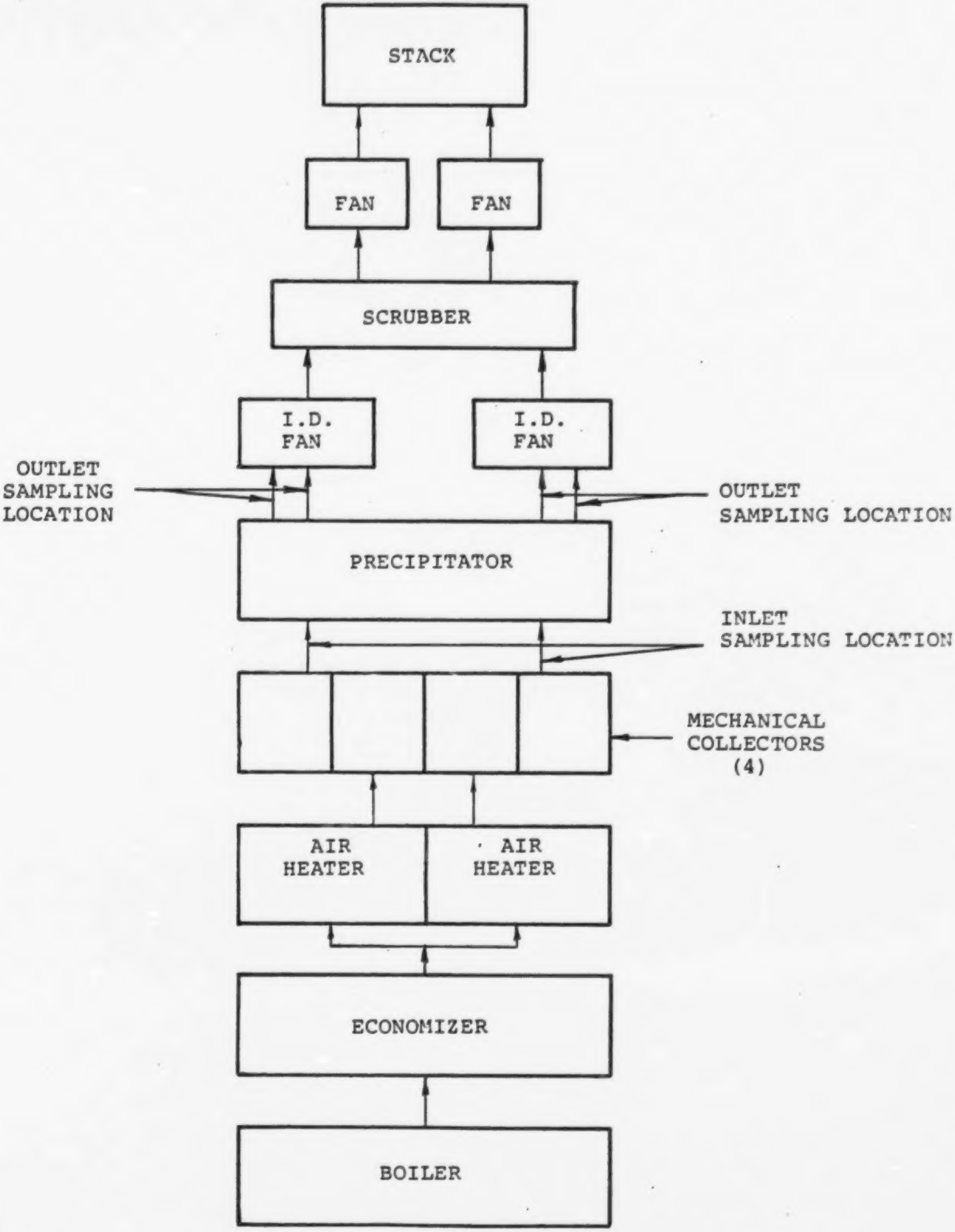

STACK
FAN
FAN
SCRUBBER
I.D. FAN
I.D. FAN
OUTLET SAMPLING LOCATION
OUTLET SAMPLING LOCATION
PRECIPITATOR
INLET SAMPLING LOCATION
MECHANICAL COLLECTORS (4)
AIR HEATER
AIR HEATER
ECONOMIZER
BOILER

FIGURE 1: AIR FLOW SCHEMATIC SHOWING SAMPLING LOCATIONS

APPENDIX V

30-DAY CEM TEST
SUPPLEMENTAL INFORMATION

EXPERIMENTAL PROCEDURES FOR THE 30-DAY TESTS

The test boiler, Unit 2 of the Hunter Generating Station of the Utah Power and Light Company, is rated at 425 megawatts electrical generating capacity. The boiler is a Combustion Engineering pulverized coal-fired unit designed for firing western bituminous coal. The steam flow at rated capacity is 972 MW (thermal) 3,318 x 10^3 lb/hr. During these 30-day tests, flue gas was sampled continuously from the flue ducts, just upstream of the air heater.

Four 30-day tests were performed on the Hunter boiler (October-December, 1982, April-May, 1983, June-July, 1983, and July-August, 1983). During each test, boiler load was recorded along with an essentially continuous record (once every four seconds) of stack emissions O_2, CO, NO, and CO_2. Also, at periodic intervals, the performance (response time, accuracy, zero and span drift, etc.) of each continuous emission monitor (CEM) was evaluated in accord with EPA procedures to ensure good performance and quality data. This section presents a description of the test procedures, the instrumentation used to measure the gaseous emissions, and the techniques for certifying the CEM system.

The emissions measurements were made using a continuous monitor fabricated by KVB, and assembled as a transportable package. Gaseous emission measurements were made with the analytical instruments listed in Table J/V-1. All measurements were made and reported on a dry basis.

TABLE J/V-1

ANALYTICAL INSTRUMENTATION

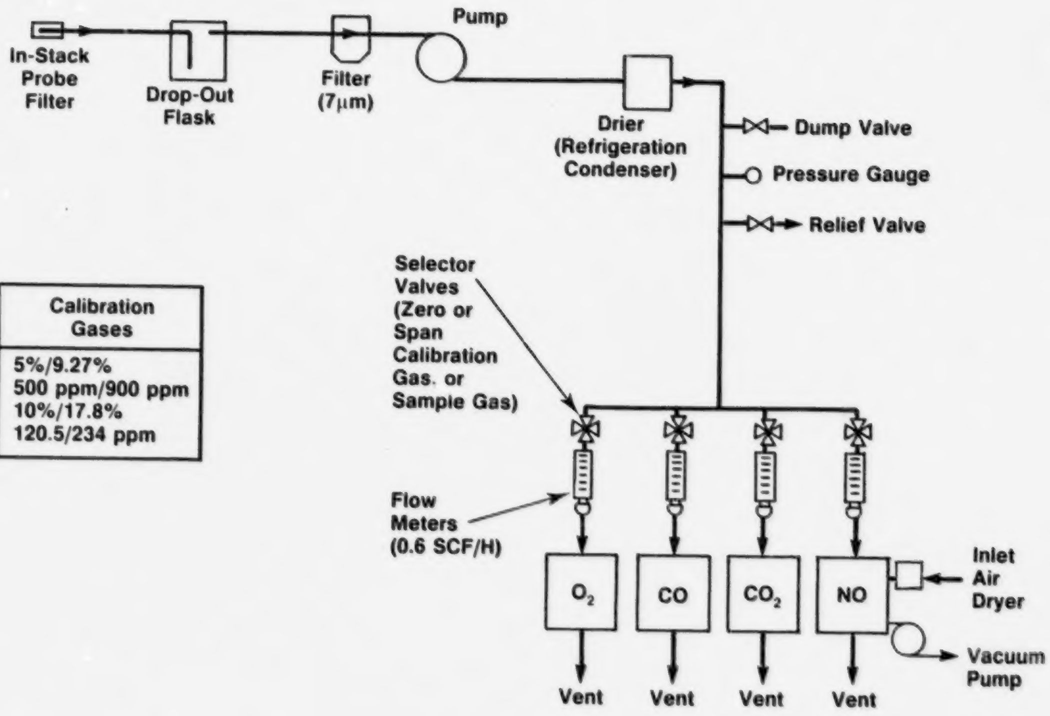
Emissions Species	Manufacturer	Measurement Method	Model No.
Nitrogen Oxides	Thermo Electron	Chemiluminescent	10AR
Oxygen	Beckman Instrument	Polarographic	742
Carbon Dioxide	Horiba Instrument	NDIR	PIR-2000
Carbon Monoxide	Horiba Instrument	NDIR	PIR-2000

The continuous monitor is equpped with analytical instruments to measure concentrations of NO, CO, CO_2, and O_2. The sample gas is delivered to the analyzers at the proper condition and flow rate through the sampling and conditioning system shown schematically in Figure J/V-1. A probe with a 0.7 micrometer sintered stainless steel filter was installed in the stack to sample the flue gas. The following paragraphs describe the analytical instrumentation.

Nitrogen Oxides

The oxides of nitrogen monitoring instrument used was a Thermo Electron chemiluminescent nitric oxide analyzer. The operational basis of the instrument is the chemiluminescent reaction of NO and O_3 to form NO_2 in an excited state which gives off its excess energy in the form of chemical luminiescence as it returns to the ground state. This chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier tube, the output of which is electronically processed so that it is linearly proportional to the NO concentration.

Air for the ozonator is drawn from ambient through an air dryer and a 10 micrometer filter element. Flow control for the instrument is accomplished by means of a small bellows pump mounted on the vent of the instrument downstream of a separator which insures that no water collects in the pump.


Pump
In-Stack
Probe
Filter
Drop-Out
Flask
Filter
(7μm)
Drier
(Refrigeration
Condenser)
Dump Valve
Pressure Gauge
Relief Valve
Selector
Valves
(Zero or
Span
Calibration
Gas. or
Sample Gas)
Flow
Meters
(0.6 SCF/H)
O2
CO
CO2
NO
Inlet
Air
Dryer
Vacuum
Pump
Vent
Vent
Vent
Vent

Instrument	Operating Range	Calibration Gases
O_2	0-10%	5%/9.27%
CO	0-1000 ppm	500 ppm/900 ppm
CO_2	0-20%	10%/17.8%
NO	0-250 ppm	120.5/234 ppm

Figure J/V-1
Schematic of Continuous Monitor Sampling
and Conditioning System

The basic analyzer is sensitive only to NO molecules. To measure NO_x (i.e., NO + NO_2), the NO_2 is first converted to NO. This is accomplished by a converter which is included with analyzer. The conversion occurs as the gas passes through a thermally insulated, resistance heated, stainless steel coil. With the application of heat, NO_2 molecules in the sample gas are reduced to NO molecules, and the analyzer then reads NO_x. NO_2 is obtained by the difference in readings obtained with and without the converter in operation.

Specifications for the Nitrogen Oxides Analyzer

Accuracy: 1% of full scale
Span drift: ± 1% of full scale in 24 hours
Zero drift: ± 1 ppm in 24 hours
Power requirements: 115 ± 10 VAC, 60 Hz, 1000 watts
Response: 90% of F.S. in 1 sec (NO_x mode); 0.7 sec (NO mode)
Output: 4-20 ma
Sensitivity: 0.5 ppm
Linearity: ± 1% of full scale
Vacuum detector operation
Ranges: 2.5, 10, 25, 100, 250, 1000, 2500, 20,000 ppm F.S.

Only the NO concentration was measured during this program. Because of the added complexity of heated sample lines and controllers necessary for measuring NO_2 and the small percentage of NO_2 in the flue gas, based on previous tests (Ref. 1, 2 and 3), it was decided that only NO measurement was necessary. Therefore, an unheated sample line was installed, and the moisture was removed from the sample gas by a dropout flask and a refrigerated condenser.

Carbon Monoxide and Carbon Dioxide

Carbon monoxide (CO) and carbon dioxide (CO_2) concentrations were measured by Horiba Instruments PIR-2000 short-path-length nondispersive infrared (NDIR) analyzers. These instruments measure the difference in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wave length absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale of zero to 100% and is then related to the concentration of the species of interest by calibration curves supplied with the instrument. A linearizer was supplied with the CO analyzer to provide a linear output over the range of interest. The operating ranges for the CO analyzer are zero to 500, zero to 1000, and zero to 2000 ppm, and the ranges for the CO_2 analyzer are zero to 5, zero to 10, and zero to 20%.

Specifications for the Carbon Monoxide and Carbon Dioxide Analyzers

Accuracy; 1% of full scale
Repeatability: ± 0.5% of full scale
Zero drift: ± 1% of full scale in 24 hours
Span drift: ± 1% of full scale in 24 hours
Response time: selectable - 90% of full scale in 0.5, 1.2, 3, or 5 seconds
Power requirements: 115 VAC ± 10%, 60 Hz
Warm up time: 30 minutes
Output: 0-10 mV

Oxygen

A Beckman Model 742 oxygen analyzer was used to continuously determine the oxygen content of the flue gas sample. The oxygen measuring element contains a silver anode and gold cathode that are protected from the sample by a thin membrane of Teflon™. An aqueous KCl solution is retained in the sensor by the membrane and serves as an electrolytic agent. As Teflon™ is permeable to gases, oxygen will diffuse from the sample to the cathode in the following oxidation-reduction reaction:

Cathode reaction: $O_2 + 2H_2O + 4e \rightarrow 4OH$
Anode reaction: $4Ag + 4Cl \rightarrow 4AgCl + 4e$

With an applied potential between the cathode and anode, oxygen will be reduced at the cathode causing a current to flow. The magnitude of this current is proportional to the partial pressure of oxygen present in the sample. The instrument has operating ranges of zero to 1%, zero to 10%, and zero to 25% oxygen.

Specifications for the Oxygen Analyzer

Accuracy: ± 1% of full scale or ± 0.05 O_2, whichever is greater
Sensor stability: ± 1% of full scale per 24 hours
Response time: 90% in 20 seconds
Output: 0-10 mV
Power requirements: 120/110 VAC, 60 Hz

Data Recording

The measurements from the gaseous analyzers were continuously recorded on dual-pen strip chart recorders, as well as an automatic data logger and magnetic tape cassettes. These instruments are described in the following paragraphs:

- Strip-Chart Recorders

  Three dual-pen Linear Instruments Corp. Model 432 strip chart recorders were installed in the continuous monitor. Two recorders were used to record the analyzer outputs and the third recorder was used as a back-up.

Specifications for the Strip-Chart Recorders

Recorder type: Null balance DC Servo
Input span: Base span 1 mV to 100 VDC

Accuracy: ± 0.5 percent
Temperature stability: 1 μV/°C
Response: 0.5 sec over full 250 mm span
Zero: Right hand zero, 100% zero suppression
Chart drive: 12 speeds
Chart width: Two channel crossover: 250 mm
Dimensions: 17.8 cm (7") H x 44.5 cm (17.5) W x 30.5 cm (12") D
Power requirements: 115/230 VAC, 60 Hz, <20 watts
Weight: 11.4 kg (25 lb)

- Automatic Data Logger

The analyzer outputs were continuously recorded on a Monitor Lab Model 9300 microprocessor-based data logger. This data logger has the capability of recording 40 input channels. The data for each analyzer was printed, along with the exact time and date, in a digital form on a built-in inkless printer. The data logger was programmed to sample each analyzer every 4 seconds and print out averages every 15 minutes. The digital printout lists the number of samples in each averaging period.

Specifications for the Automatic Data Logger

Inputs: Up to 40 channels of analog voltage, current and temperature inputs can be accommodated in the mainframe.
Voltage ranges: ± 30,000 mV, ± 300.00 mV, ± 3.000 V, ± 12.000 V, Autorange
Resolution: 1 μV on 30.000 mV range
Accuracy: ± 0.02% of Reading, ± 0.01% of range, ± 1 digit
Power: 115/230 V ± 10%, 60 Hz, <125 watts
Dimensions: 18 cm (H) x 48.3 cm (W) x 56 cm (D) (17" x 19" x 22")
Weight: 18.2 kg (40 lb)

- Digital Tape Cassette Recorder

Data from the automatic data logger were recorded on magnetic tape cassettes with a Techtran Model 816 recorder. This recorder stored all gaseous emissions data on tape for subsequent use.

Specifications for the Tape Cassette Recorder

Storage capacity: 145,000 characters per cassette
Storage media: Phillips-type magnetic tape cassette
Tape speed: 20 ips read/write; 120 ips rewind
Size: 13 cm (H) x 18 cm (W) x 28 cm (D) (5" x 7-1/4" x 11")
Weight: 2.7 kg (6 lb)
Temperature range: 10° to 40°C
Power requirements: 115 VAC 47-63 Hz; 30 watts

Gaseous emissions data were measured continuously and recorded on an automatic data logger, as well as on strip-chart recorders and a magnetic tape recorder as already described. All gaseous emissions measurements were made and reported on a dry basis. Fifteen minute averages (about 225 data points for each instrument) of NO, O_2, CO_2, and CO emissions were recorded on tape, while strip-chart records were used to verify the data logger tapes and to fill in any gaps in the data from the automatic data logger. A daily log of emissions and boiler operating data was kept by a technician on-site. These data were later fed to a computer for data analysis.

The Conversion of NO_x units from ppm to ng/J was made using the procedure outlined in the Federal Register (Vol. 44, No. 113/Monday, June 11, 1979, paragraph 5.3, "Calculation of Emission Rate"). The NO emission rates for this unit were calculated from the following equation:

$$E = (C_d)(F_d)\left(\frac{20.9}{20.9 - \%\ O_2}\right)$$

Where:

E = pollutant emission rate, ng/

C_d = pollutant concentration, ng/scm

To convert from ppm (NO_x) to ng/scm, multiply by 1.912×10^6.

F_d = fuel firing factor (i.e., the ratio of gas volume released during combustion divided by the heat content of the fuel) dscm/J. F_d for bituminous coal is 2.63×10^{-7} dscm/J.

The subscript d represents a dry measurement of gaseous concentration.

NO emissions were measured on a dry basis and the emission rates reported herein were calculated based on the molecular weight of NO_2 (NO_x as NO_2). The boiler steam load is tabulated in units of thermal megawatts (the SI equivalent of Btu/hr). Thermal megawatts (MW_{th}) were calculated by multiplying the boiler steam flow, lb/hr (obtained from the daily log sheet) by the enthalpy of the steam (approximately 10^3 Btu/lb) and by the conversion factor for Btu/hr to watts, 0.293. Note that megawatts thermal is the boiler steam load in SI energy units, and should not be confused with the gross electrical generator output which is also expressed in megawatts.

After the preliminary screening, the data were fed to the computer and a listing of 15-minute averages was compiled. Each 15-minute average was corrected to 3 percent O_2 basis and these data were then used to compile 24-hour averages for the entire test period. The data is too voluminous to include here. However, as an example, a partial listing of the 15-minute averages may be found at the end of this appendix.

CONTINUOUS MONITOR CERTIFICATION TESTS

Following shipment to the test site, the monitoring system was installed and certification tests were performed according to EPA's Performance Specification 2 and 3 (PS2 and PS3), 40 CFR 60. These specifications establish minimum performance criteria that the NO monitoring system must meet in terms of eight parameters: accuracy, calibration error, two- and 24-hour zero drifts, two- and 24-hour calibration drifts, response time, and operational period.

For each of four tests, the continuous monitor system was installed and instruments were initially calibrated shortly after arrival at the test site. The monitor performance certification tests were performed at the start and at the finish of each 30-day emissions test. Certification work generally required about seven days. Schedules of daily events for the certification tests are presented in Tables J/V-2 through J/V-5.

Certified calibration gases were obtained from Scott Environmental Technology, Inc. The calibration gases included zero gas as well as 50% and 90% (of full scale) span gases for the NO, CO_2, CO, and O_2 analyzers. In addition to the certified analysis supplied by the vendor, flask samples of the NO calibration gas were sent to an independent laboratory for analysis.

Relative accuracy tests for the NO analyzer were performed as outlined in PS2 using EPA Reference Method 7 (phenoldisulfonic acid [PDS] colorimetric) as the standard. Generally, nine sets of three PDS flasks (27 in all) were collected at one hour intervals at the beginning of each 30-day test, and the process was repeated at the end of each 30-day test period. The NO_x span gases (various blends of NO in N_2) were also analyzed by the PDS method, and the results are shown in Table J/V-6. The results of the relative accuracy determination showed that the NO instrument exceeded the accuracy requirements of PS2.

TABLE J/V-2 (pg 1 of 2)
SCHEDULE OF CERTIFICATION TEST EVENTS
FIRST 30 DAY CEM TEST

Date	Time	Event
10-22-82	1100	Initial 2 hour zero and calibration reading
10-22-82	1300	1st 2 hour zero and calibration drift point
10-22-82	1500	2nd 2 hour zero and calibration drift point
10-22-82	1700	3rd 2 hour zero and calibration drift point
10-23-82	0900	Initial 24 hour zero and calibration reading
10-24-82	0900	1st 24 hour zero and calibration drift point
10-25-82	0900	Initial 2 hour zero and calibration reading 2nd 24 hour zero and calibration drift point
10-25-82	1100	4th 2 hour zero and calibration drift point
10-25-82	1300	5th 2 hour zero and calibration drift point
10-25-82	1500	6th 2 hour zero and calibration drift point
10-26-82	0900	Initial 2 hour zero and calibration drift reading 3rd 24 hour zero and calibration drift point
10-26-82	1100	7th 2 hour zero and calibration drift point
	1300	8th 2 hour zero and calibration drift point
	1500	9th 2 hour zero and calibration drift point
10-27-82	0900	Initial 2 hour zero and calibration drift reading 4th 24 hour zero and calibration drift point
10-27-82	1100	10th 2 hour zero and calibration drift point
10-27-82	1300	11th 2 hour zero and calibration drift point
10-27-82	1500	12th 2 hour zero and calibration drift point
10-27-82	1700	13th 2 hour zero and calibration drift point
10-28-82	0900	Initial 2 hour zero and calibration drift reading 5th 24 hour zero and calibration drift point
10-28-82	1100	14th 2 hour zero and calibration drift point
10-28-82	1300	15th and final 2 hour zero and calibration drift point
10-29-82	0900	6th 24 hour zero and calibration drift point
10-30-82	0900	7th and final zero and calibration drift point

TABLE J/V-2 (pg 2 of 2)

Date	Time	Event
10-27-82		Initial Relative Accuracy Test
	1030	1st set of relative accuracy samples taken
	1130	2nd set of relative accuracy samples taken
	1230	3rd set of relative accuracy samples taken
	1330	4th set of relative accuracy samples taken
	1430	5th set of relative accuracy samples taken
	1530	6th set of relative accuracy samples taken
	1630	7th set of relative accuracy samples taken
	1730	8th set of relative accuracy samples taken
	1830	9th set of relative accuracy samples taken
11-01-82		Instrument Response Time Sheets
12-02-82		Final Relative Accuracy Test
12-02-82	1200	1st set of relative accuracy samples taken
12-02-82	1300	2nd set of relative accuracy samples taken
12-02-82	1400	3rd set of relative accuracy samples taken
12-02-82	1500	4th set of relative accuracy samples taken
12-02-82	1600	5th set of relative accuracy samples taken
12-02-82	1700	6th set of relative accuracy samples taken
12-02-82	1800	7th set of relative accuracy samples taken
12-02-82	1900	8th set of relative accuracy samples taken
12-02-82	2000	9th set of relative accuracy samples taken

TABLE J/V-3 (pg 1 of 2)
SCHEDULE OF CERTIFICATION TEST EVENTS
SECOND 30 DAY CEM TEST

Date	Time	Event
4-8-83	0600	Initial 2 hour zero and 24 hour zero and calibration reading
4-8-83	0800	1st 2 hour zero and calibration drift point
4-8-83	1000	2nd 2 hour zero and calibration drift point
4-8-83	1200	3rd 2 hour zero and calibration drift point
4-8-83	1400	4th 2 hour zero and calibration drift point
4-9-83	0600	1st 24 hour zero and calibration drift point
4-9-83	0600	Initial 2 hour zero and 24 hour zero and calibration reading
4-9-83	0800	5th 2 hour zero and calibration drift point
4-9-83	1000	6th 2 hour zero and calibration drift point
4-9-83	1200	7th 2 hour zero and calibration drift point
4-9-83	1400	8th 2 hour zero and calibration drift point
4-10-83	0600	2nd 24 hour zero and calibration drift point
4-10-83	0600	Initial 2 hour zero and 24 hour zero and calibration reading
4-10-83	0800	9th 2 hour zero and calibration drift point
4-10-83	1000	10th 2 hour zero and calibration drift point
4-10-83	1200	11th 2 hour zero and calibration drift point
4-10-83	1400	12th 2 hour zero and calibration drift point
4-11-83	0600	3rd 24 hour zero and calibration drift point
4-11-83	0600	Initial 2 hour zero and calibration drift reading
4-11-83	1000	13th 2 hour zero and calibration drift point
4-11-83	1200	14th 2 hour zero and calibration drift point
4-11-83	1400	15th and final 2 hour zero and calibration drift point
4-12-83	0600	4th 24 hour zero and calibration drift point
4-13-83	0600	5th 24 hour zero and calibration drift point
4-14-83	0600	6th 24 hour zero and calibration drift point
4-15-83	0600	7th and final 24 hour zero and calibration drift point

TABLE J/V-3 (pg 2 of 2)

Date	Time	Event
4-11-83		Calibration error sheets
4-16-83		Initial Relative Accuracy Test
	0850	1st set of relative accuracy samples taken
	0950	2nd set of relative accuracy samples taken
	1050	3rd set of relative accuracy samples taken
	1150	4th set of relative accuracy samples taken
	1250	5th set of relative accuracy samples taken
	1350	7th set of relative accuracy samples taken
	1450	7th set of relative accuracy samples taken
	1550	8th set of relative accuracy samples taken
	1650	9th set of relative accuracy samples taken
4-16-83		Instrument Response Time Sheets
5-10-83		Final Relative Accuracy Test
	0910	1st set of relative accuracy samples taken
	1010	2nd set of relative accuracy samples taken
	1110	3rd set of relative accuracy samples taken
	1210	4th set of relative accuracy samples taken
	1310	5th set of relative accuracy samples taken
	1410	6th set of relative accuracy samples taken
	1510	7th set of relative accuracy samples taken
	1610	8th set of relative accuracy samples taken
	1710	9th set of relative accuracy samples taken

TABLE J/V-4 (pg 1 of 2)
SCHEDULE OF CERTIFICATION TEST EVENTS
THIRD 30 DAY CEM TEST

Date	Time	Event
6-19-83	0900	Initial 4 hour zero and calibration reading
6-20-83	0900	1st 24 hour zero and calibration drift point
6-21-83	0900	2nd 24 hour zero and calibration drift point
6-21-83	1000	Initial 2 hour zero and calibration reading
6-21-83	1200	1st 2 hour zero and calibration drift point
6-21-83	1400	2nd 2 hour zero and calibration drift point
6-21-83	1600	3rd 2 hour zero and calibration drift point
6-22-83	0900	3rd 24 hour zero and calibration drift point
6-22-83	1000	Initial 2 hour zero and calibration reading
6-22-83	1300	4th 2 hour zero and calibration drift point
6-22-83	1400	5th 2 hour zero and calibration drift point
6-23-83	0900	4th 24 hour zero and calibration drift point
6-23-83	0900	Initial 2 hour zero and calibration reading
6-23-83	1100	6th 2 hour zero and calibration drift point
6-23-83	1300	7th 2 hour zero and calibration drift point
6-23-83	1500	8th 2 hour zero and calibration drift point
6-24-83	0900	5th 24 hr zero and calibration drift point
6-24-83	1000	Initial 2 hour zero and calibration drift point
6-24-83	1200	9th 2 hour zero and calibration drift point
6-24-83	1400	10th 2 hour zero and calibration drift point
6-24-83	1600	11th 2 hour zero and calibration drift point
6-25-83	0900	6th 24 hour zero and calibration drift point
6-25-83		Instrument response time sheets
6-25-83		Instrument calibration error sheets
6-25-83	0900	Initial 2 hr zero and calibration reading
6-25-83	1100	12th 2 hr zero and calibration drift point
6-25-83	1300	13th 2 hr zero and calibration drift point
6-25-83	1500	14th 2 hr zero and calibration drift point

TABLE J/V-4 (pg 2 of 2)

Date	Time	Event
6-25-83	1700	15th 2 hour zero and calibration drift point
6-26-83	0900	7th 24 hour zero and calibration drift point
6-29-83		Initial relative accuracy tests
6-29-83	1000	1st set of relative accuracy samples taken
6-29-83	1100	2nd set of relative accuracy samples taken
6-29-83	1200	3rd set of relative accuracy samples taken
6-29-83	1300	4th set of relative accuracy samples taken
6-29-83	1400	5th set of relative accuracy samples taken
6-29-83	1500	6th set of relative accuracy samples taken
6-29-83	1600	7th set of relative accuracy samples taken
6-29-83	1700	8th set of relative accuracy samples taken
6-29-83	1800	9th set of relative accuracy samples taken
7-20-83		Final relative accuracy test
7-20-83	0800	1st set of relative accuracy samples taken
7-20-83	0900	2nd set of relative accuracy samples taken
7-20-83	1000	3rd set of relative accuracy samples taken
7-20-83	1100	4th set of relative accuracy samples taken
7-20-83	1200	5th set of relative accuracy samples taken
7-20-83	1300	6th set of relative accuracy samples taken
7-20-83	1400	7th set of relative accuracy samples taken
7-20-83	1500	8th set of relative accuracy samples taken
7-20-83	1600	9th set of relative accuracy samples taken

TABLE J/V-5 (pg 1 of 2)
SCHEDULE OF CERTIFICATION TEST EVENTS
FOURTH 30 DAY CEM TEST

Date	Time	Event
7-25-83	0900	Initial 4 hour zero and calibration reading
7-26-83	0900	1st 24 hour zero and calibration drift point
7-26-83	0900	Initial 2 hour zero and calibration reading
7-26-83	1100	1st 2 hour zero and calibration drift point
7-26-83	1300	2nd 2 hour zero and calibration drift point
7-26-83	1500	3rd 2 hour zero and calibration drift point
7-26-83	1700	4th 2 hour zero and calibration drift point
7-27-83	0900	2nd 24 hour zero and calibration drift point
7-27-83		Instrument response time sheets
7-27-83		Instrument calibration error sheets
7-27-83	0900	Initial 2 hour zero and calibration drift point
7-27-83	1100	5th 2 hour zero and calibration drift point
7-27-83	1300	6th 2 hour zero and calibration drift point
7-27-83	1500	7th 2 hour zero and calibration drift point
7-27-83	1700	8th 24 hour zero and calibration drift point
7-28-83	0900	3rd 24 hour zero and calibration drift point
7-28-83	0900	Initial 2 hour zero and calibration reading
7-28-83	1100	9th 2 hour zero and calibration drift point
7-28-83	1300	10th 2 hour zero and calibration drift point
7-28-83	1500	11th 2 hour zero and calibration drift point
7-28-83	1700	12th 2 hour zero and calibration drift point
7-29-83	0900	4th 24 hr zero and calibration drift point
7-29-83	0900	Initial 2 hr zero and calibration reading
7-29-83	1100	13th 2 hr zero and calibration drift point
7-29-83	1300	14th 2 hr zero and calibration drift point
7-29-83	1500	15th 2 hr zero and calibration drift point

TABLE J/V-5 (pg 2 of 2)

Date	Time	Event
7-30-83	0900	5th 24 hr zero and calibration drift point
7-31-83	0900	6th 24 hr zero and calibration drift point
8-1-83	0900	7th 24 hr zero and calibration drift point
7-29-83		Initial relative accuracy tests
7-29-83	1000	1st set of relative accuracy samples taken
7-29-83	1100	2nd set of relative accuracy samples taken
7-29-83	1200	3rd set of relative accuracy samples taken
7-29-83	1300	4th set of relative accuracy samples taken
7-29-83	1400	5th set of relative accuracy samples taken
7-29-83	1500	6th set of relative accuracy samples taken
7-29-83	1600	7th set of relative accuracy samples taken
7-29-83	1700	8th set of relative accuracy samples taken
7-29-83	1800	9th set of relative accuracy samples taken
8-25-83		Final relative accuracy test
8-25-83	0900	1st set of relative accuracy samples taken
8-25-83	1000	2nd set of relative accuracy samples taken
8-25-83	1100	3rd set of relative accuracy samples taken
8-25-83	1200	4th set of relative accuracy samples taken
8-25-83	1300	5th set of relative accuracy samples taken
8-25-83	1400	6th set of relative accuracy samples taken
8-25-83	1500	7th set of relative accuracy samples taken
8-25-83	1600	8th set of relative accuracy samples taken
8-25-83	1700	9th set of relative accuracy samples taken

TABLE J/V-6

REFERENCE METHOD 7 (PDSA) TESTS OF NO_x CALIBRATION GAS

	Flask No.	Vendor-Stated Calibration Gas Concentration (ppm)	PDSA Data. Method 7 Results (ppm)
Test No. 1	1358	405.5	398
	1300		400
	1308		424
			Avg. 407
	1182	405.5	424
	1161		411
			Avg. 412
Test No. 2	1037	862	899
	1053	862	903
	1322	503	477
	1384	503	474
Test No. 3*			
Test No. 4	1449	862	878
	1445	862	841
	3030	455	464
	3473	455	449

* Test Nos. 2, 3, and 4 were performed in rapid order with very little time in between tests. Because of this, Test 3 used the same calibration gas cylinders as were used in test 2 and 4. Therefore, no PDSA data are presented here for Test No. 3.

TABLE J/V-7
TABULATION OF 15-MINUTE CEM DATA

SELECTED DATA FROM
TEST NO. 2

As an example, the next few pages present data from about two days of the second thirty day test.

The last column in each of the following pages is called the "A Code" and is explained below.

Code		Explanation
A	-	Testing Begins
B	-	Testing Ends
C	-	Instrument Calibrations
D	-	NO Instrument Out of Service (Maintenance)
E	-	O_2 Instrument Out of Service (Maintenance)
F	-	CO_2 Instrument Out of Service (Maintenance)
G	-	CO Instrument Out of Service (Maintenance)
H	-	Boiler (Or Unit) Out of Service
I	-	Continuous Monitor Certification Tests
J	-	Continuous Monitor Out of Service (Maintenance)
K	-	Power Failure

UTAH P&L UNIT 2 TEST 2

15 MIN DATA
DRY STACK GAS CONCENTRATION

DATE 1983	TIME	LOAD MWTH	LOAD MWE	O2 VOL% MEAS	CO2 VOL% MEAS	CO PPMV MEAS	NO PPMV MEAS	NO PPMV 3%O2	CO NG/J --	NO NG/J --	CODE
4/8	15	--	--	5.6	13.2	21	362	423	9	245	
4/8	30	--	--	5.3	13.5	22	365	418	9	242	
4/8	45	--	--	5	14	22	363	408	9	236	
4/8	100	514.8	246	5.2	13.7	22	363	414	9	239	
4/8	115	--	--	5.3	13.6	22	361	414	9	239	
4/8	130	--	--	5	14	23	364	410	9	237	
4/8	145	--	--	5	13.4	25	343	386	10	223	
4/8	200	541.5	258	4.5	14.5	26	347	379	10	219	
4/8	215	--	--	4.3	14.8	26	347	374	10	216	
4/8	230	--	--	4.2	14.9	27	348	373	10	216	
4/8	245	--	--	4.3	14.9	35	341	368	13	213	
4/8	300	573.7	276	4.7	14.2	28	342	378	11	218	
4/8	315	--	--	5	13.9	29	336	378	12	218	
4/8	330	--	--	4.7	14.3	42	339	374	16	216	
4/8	345	--	--	4.4	14.7	44	333	361	17	209	
4/8	400	588.1	283	4.6	14.4	60	333	365	23	211	
4/8	415	--	--	4.8	14.3	2	330	367	1	212	
4/8	430	--	--	4.3	14.8	45	344	371	17	214	
4/8	445	--	--	5.4	13.3	27	357	412	11	238	
4/8	500	607.7	296	5.4	13.4	28	361	417	11	241	
4/8	515	--	--	5.3	13.6	32	359	412	13	238	
4/8	530	--	--	4.8	14.2	51	364	404	20	234	
4/8	545	--	--	4.7	14.3	47	366	404	18	234	
4/8	600	647.5	317	4.5	14.5	46	367	400	18	231	
4/8	615	--	--	0	0	0	0	0	0	0	C
4/8	630	--	--	4.9	13.8	51	355	397	20	229	
4/8	645	--	--	2.8	17.9	160	294	291	56	168	
4/8	700	655.7	321	2.7	17.7	447	236	232	155	134	
4/8	715	--	--	2.6	17.8	633	281	275	219	159	
4/8	730	--	--	3.2	17.1	31	364	368	11	213	
4/8	745	--	--	3.6	16.6	20	294	304	7	176	
4/8	800	655.1	319	2.9	17.5	32	288	286	11	165	
4/8	815	--	--	3.1	17.2	29	287	289	10	167	
4/8	830	--	--	2.6	17.9	38	292	286	13	165	
4/8	845	--	--	2.5	18	29	291	283	10	164	
4/8	900	661.3	320	2.7	17.7	29	293	288	10	166	
4/8	915	--	--	2.8	17.5	30	288	285	10	165	
4/8	930	--	--	2.9	17.5	29	287	285	10	165	
4/8	945	--	--	2.6	17.9	33	284	278	11	161	
4/8	1000	657.8	320	2.8	17.7	22	287	284	8	164	
4/8	1015	--	--	2.8	17.6	18	281	278	6	161	
4/8	1030	--	--	2.6	17.8	28	285	279	10	161	
4/8	1045	--	--	2.7	17.7	23	290	285	8	165	
4/8	1100	660.7	321	2.6	17.6	26	293	287	9	166	
4/8	1115	--	--	3	17.4	26	291	291	9	168	
4/8	1130	--	--	2.5	18	52	285	277	18	160	
4/8	1145	--	--	2.6	17.8	0	275	269	0	155	
4/8	1200	658.7	321	2.8	17.4	59	284	281	21	162	

UTAH P&L UNIT 2 TEST 2

15 MIN DATA
DRY STACK GAS CONCENTRATION

DATE 1983	TIME	LOAD MWTH	LOAD MWE	O2 VOL% MEAS	CO2 VOL% MEAS	CO PPMV MEAS	NO PPMV MEAS	NO PPMV 3%O2	CO NG/J --	NO NG/J --	CODE
4/8	1215	--	--	0	0	0	0	0	0	0	C
4/8	1230	--	--	2.6	17.8	0	275	269	0	155	
4/8	1245	--	--	2	18.6	97	271	257	32	149	
4/8	1300	656.9	320	2.3	18.2	52	276	266	18	154	
4/8	1315	--	--	3.1	17.1	0	274	276	0	160	
4/8	1330	--	--	2.2	18.3	40	267	256	14	148	
4/8	1345	--	--	2.2	18.3	12	264	253	4	146	
4/8	1400	632.3	308	2.6	17.9	13	270	264	4	153	
4/8	1415	--	--	0	0	0	0	0	0	0	C
4/8	1430	--	--	2.6	19.2	10	269	263	3	152	
4/8	1445	--	--	4.2	17	21	274	294	8	170	
4/8	1500	633.5	306	2.5	19.4	30	283	275	10	159	
4/8	1515	--	--	2.8	19	25	281	278	9	161	
4/8	1530	--	--	2.4	19.5	7	284	275	2	159	
4/8	1545	--	--	2.5	19.4	31	287	279	11	161	
4/8	1600	626.4	301	2.6	19.2	29	284	278	10	161	
4/8	1615	--	--	3.1	18.5	21	280	282	7	163	
4/8	1630	--	--	3	18.7	20	286	286	7	165	
4/8	1645	--	--	3.2	18.4	19	293	296	7	171	
4/8	1700	560.8	267	3.3	18.2	18	296	301	6	174	
4/8	1715	--	--	3.5	17.9	18	290	298	7	172	
4/8	1730	--	--	3.2	18.3	18	296	299	6	173	
4/8	1745	--	--	3.4	18.1	19	293	300	7	173	
4/8	1800	544.4	258	4.5	16.5	19	308	336	7	194	
4/8	1815	--	--	5.1	15.8	18	307	348	7	201	
4/8	1830	--	--	4.4	16.7	19	314	340	7	197	
4/8	1845	--	--	4.2	17	20	316	339	8	196	
4/8	1900	536.5	254	4	17.3	19	317	336	7	194	
4/8	1915	--	--	3.4	18.2	31	305	312	11	180	
4/8	1930	--	--	3.1	18.5	28	310	312	10	180	
4/8	1945	--	--	2.6	19.2	52	299	293	18	169	
4/8	2000	601.5	290	2.7	19.2	34	298	293	12	169	
4/8	2015	--	--	2.9	18.9	32	289	287	11	166	
4/8	2030	--	--	2.5	19.6	36	291	283	12	164	
4/8	2045	--	--	2.3	19.8	0	282	271	0	157	
4/8	2100	592.7	284	2.4	19.7	19	290	281	6	162	
4/8	2115	--	--	2.8	19.1	32	287	284	11	164	
4/8	2130	--	--	3.7	17.7	19	303	315	7	182	
4/8	2145	--	--	3.3	18.3	20	300	305	7	176	
4/8	2200	552.9	264	3.2	18.5	22	299	302	8	175	
4/8	2215	--	--	0	0	0	0	0	0	0	C
4/8	2230	--	--	3.9	18.7	24	305	321	9	186	
4/8	2245	--	--	3.8	18.9	23	306	320	9	185	
4/8	2300	525.9	250	4.1	18.4	24	309	329	9	190	
4/8	2315	--	--	6.2	15.4	21	342	416	9	240	
4/8	2330	--	--	6.5	14.8	22	348	432	10	250	
4/8	2345	--	--	6.7	14.6	21	349	439	9	254	
4/8	2400	493.4	233	6.7	14.6	22	350	441	10	255	

UTAH P&L UNIT 2 TEST 2

15 MIN DATA
DRY STACK GAS CONCENTRATION

DATE 1983	TIME	LOAD MWTH	LOAD MWE	02 VOL% MEAS	CO2 VOL% MEAS	CO PPMV MEAS	NO PPMV MEAS	NO PPMV 3%02	CO MG/J --	NO MG/J --	CODE
4/9	15	--	--	6.7	14.6	22	345	434	10	251	
4/9	30	--	--	6.5	14.9	23	348	432	10	250	
4/9	45	--	--	6.4	15	23	348	429	10	248	
4/9	100	495.5	234	6.5	14.9	23	349	433	10	250	
4/9	115	--	--	6.7	14.6	24	343	432	11	250	
4/9	130	--	--	6.4	15	24	349	430	10	249	
4/9	145	--	--	6.4	15	24	349	430	10	249	
4/9	200	493.7	233	6.5	14.9	24	349	433	11	250	
4/9	215	--	--	6.7	14.5	26	336	423	12	245	
4/9	230	--	--	5.9	15.8	27	327	390	11	225	
4/9	245	--	--	5.6	16.2	28	342	400	12	231	
4/9	300	532.7	252	5.5	16.4	28	342	397	11	229	
4/9	315	--	--	6	15.7	26	351	421	11	243	
4/9	330	--	--	5.7	16	27	350	412	11	238	
4/9	345	--	--	5.6	16.2	27	352	411	11	238	
4/9	400	505.7	239	5.6	16.2	27	355	415	11	240	
4/9	415	--	--	5.7	16	27	347	408	11	236	
4/9	430	--	--	5.8	15.9	27	351	416	11	240	
4/9	445	--	--	5.8	15.9	26	352	417	11	241	
4/9	500	504	239	5.6	16.2	27	353	413	11	239	
4/9	515	--	--	5.7	16	27	347	408	11	236	
4/9	530	--	--	5.2	16.9	27	349	398	11	230	
4/9	545	--	--	5.4	16.4	26	346	399	11	231	
4/9	600	513.3	244	6.1	15.4	27	338	408	12	236	
4/9	615	--	--	0	0	0	0	0	0	0	C
4/9	630	--	--	6.7	16	20	336	423	9	245	
4/9	645	--	--	6	17.2	21	329	395	9	228	
4/9	700	528.3	252	4.6	19.6	21	312	342	8	198	
4/9	715	--	--	4.4	20.2	21	289	313	8	181	
4/9	730	--	--	2.5	24	12	291	283	4	164	
4/9	745	--	--	2.3	17.6	71	291	280	24	162	
4/9	800	620	299	2.5	17.6	37	287	279	13	161	
4/9	815	--	--	2.7	17.4	53	282	277	18	160	
4/9	830	--	--	2.5	17.5	49	284	276	17	160	
4/9	845	--	--	2.5	17.6	0	282	274	0	158	
4/9	900	627.6	304	2.5	17.5	36	289	281	12	162	
4/9	915	--	--	2.8	17.2	29	289	286	10	165	
4/9	930	--	--	2.6	17.5	45	295	289	16	167	
4/9	945	--	--	2.5	17.6	54	295	287	19	166	
4/9	1000	627	302	2.8	17.2	30	296	293	10	169	
4/9	1015	--	--	2.9	17.2	23	297	295	8	171	
4/9	1030	--	--	2.6	17.5	42	298	292	15	169	
4/9	1045	--	--	2.3	17.8	19	290	279	6	161	
4/9	1100	627.3	303	2.3	17.8	53	286	275	18	159	
4/9	1115	--	--	2.6	17.4	33	283	277	11	160	
4/9	1130	--	--	2.3	17.7	53	286	275	18	159	
4/9	1145	--	--	2.6	17.4	27	300	293	9	169	
4/9	1200	651.6	316	2.1	18	71	290	276	24	160	

UTAH P&L UNIT 2 TEST 2

15 MIN DATA
DRY STACK GAS CONCENTRATION

DATE 1983	TIME	LOAD MWTH	LOAD MWE	O2 VOL% MEAS	CO2 VOL% MEAS	CO PPMV MEAS	NO PPMV MEAS	NO PPMV 3%O2	CO NG/J --	NO NG/J --	CODE
4/9	1215	--	--	2.2	17.9	112	286	274	38	158	
4/9	1230	--	--	2.5	17.4	40	297	289	14	167	
4/9	1245	--	--	2.7	17.3	49	296	291	17	168	
4/9	1300	642	310	2.5	17.5	20	291	283	7	164	
4/9	1315	--	--	3.1	16.9	18	286	288	6	166	
4/9	1330	--	--	2.6	17.4	30	288	282	10	163	
4/9	1345	--	--	3	16.9	0	292	292	0	169	
4/9	1400	612.7	310	2.8	17.1	28	293	290	10	168	
4/9	1415	--	--	0	0	0	0	0	0	0	C
4/9	1430	--	--	2.6	17.8	37	281	275	13	159	
4/9	1445	--	--	3	17.3	35	287	287	12	166	
4/9	1500	592.4	295	3.4	16.8	21	295	302	8	175	
4/9	1515	--	--	4.1	16	19	298	317	7	183	
4/9	1530	--	--	4.2	15.8	19	308	330	7	191	
4/9	1545	--	--	4.3	15.6	19	312	336	7	194	
4/9	1600	547.9	282	4.5	15.4	19	312	340	7	197	
4/9	1615	--	--	4.9	14.9	18	311	348	7	201	
4/9	1630	--	--	4.7	15.2	19	317	350	7	202	
4/9	1645	--	--	4.5	15.3	21	305	333	8	192	
4/9	1700	555.8	260	4.8	15	21	314	349	8	202	
4/9	1715	--	--	4.7	15.2	20	311	343	8	198	
4/9	1730	--	--	4.4	15.5	21	315	342	8	198	
4/9	1745	--	--	4.4	15.5	21	318	345	8	199	
4/9	1800	591.6	263	4.1	15.9	21	320	341	8	197	
4/9	1815	--	--	3.4	16.8	61	304	311	22	180	
4/9	1830	--	--	3.9	16	28	307	323	10	187	
4/9	1845	--	--	4.2	15.8	21	317	340	8	197	
4/9	1900	590.1	283	3.5	16.6	22	313	322	8	186	
4/9	1915	--	--	3.7	16.3	23	308	320	8	185	
4/9	1930	--	--	4	16	22	313	331	8	191	
4/9	1945	--	--	3.9	16.2	22	312	328	8	190	
4/9	2000	602.1	281	4.1	15.9	20	317	338	8	195	
4/9	2015	--	--	3.8	16.2	22	307	321	8	186	
4/9	2030	--	--	3.6	16.6	22	310	321	8	186	
4/9	2045	--	--	3.4	16.8	23	310	317	8	183	
4/9	2100	598.9	288	3.5	16.7	21	305	314	8	182	
4/9	2115	--	--	3.6	16.5	22	296	306	8	177	
4/9	2130	--	--	2.8	17.5	28	293	290	10	168	
4/9	2145	--	--	2.8	17.5	25	291	288	9	166	
4/9	2200	588.9	288	2.7	17.6	24	290	285	8	165	
4/9	2215	--	--	0	0	0	0	0	0	0	C
4/9	2230	--	--	2.5	17.9	4	285	277	1	160	
4/9	2245	--	--	2.6	17.7	28	289	283	10	164	
4/9	2300	575.2	276	4.1	15.9	21	308	328	8	190	
4/9	2315	--	--	4.1	16	20	300	320	8	185	
4/9	2330	--	--	5.1	14.6	19	322	365	8	211	
4/9	2345	--	--	5.6	14	19	327	382	8	221	
4/9	2400	512.2	242	5.8	13.7	19	332	393	8	227	

REFERENCES FOR THIS APPENDIX

1. Maloney, K. L. et al. Systems Evaluation of the Use of Low-Sulfur Western Coal in Existing Small and Intermediate-Sized Boilers. EPA Contract No. 68-02-1863. EPA 600/7-78-153a. July 1978.

2. Cato, G. A. et al. Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers - Phase I. EPA 650/2-74-078a, NTIS No. PB 238 920. June 1975.

3. Cato, G. A. et al. Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers - Phase II. EPA 600/2-76-086a, NTIS No. PB 253 500. April 1976.

APPENDIX VI

COAL AND SLAG ANALYSIS

TABLE J/VI-1

COAL ULTIMATE ANALYSES (%, DRY BASIS)
UTAH POWER AND LIGHT COMPANY
HUNTER UNIT NO. 2

DATE	HYDROGEN	CARBON	SULFUR	NITROGEN	OXYGEN	ASH	OXYGEN/ NITROGEN
08/03/81	5.28	69.04	0.55	1.06	10.57	13.50	9.97
08/08/81	4.93	68.48	0.56	1.37	10.26	14.40	7.49
08/12/81	5.53	69.61	0.58	1.34	10.23	12.71	7.63
08/17/81	5.29	69.44	0.60	1.36	9.59	13.72	7.05
11/01/81	5.73	72.72	0.62	1.30	7.77	11.86	5.98
11/06/81	5.06	67.39	0.71	1.22	8.78	16.84	7.20
11/11/81	5.41	67.46	0.65	1.34	5.02	20.12	3.75
11/17/81	5.07	72.27	0.53	1.23	11.02	9.88	8.96
03/16/82	4.96	65.52	0.67	1.24	9.09	18.52	7.33
03/20/82	5.19	69.38	0.57	1.30	9.98	13.58	7.68
03/23/82	5.11	67.75	0.62	1.11	10.12	15.29	9.12
03/26/82	5.13	69.17	0.82	1.11	9.74	14.03	8.77
03/30/82	5.20	69.07	0.63	1.24	9.72	14.14	7.84
09/23/82	5.36	68.35	0.61	1.26	10.65	13.77	8.45
09/27/82	5.04	67.14	0.58	1.16	10.46	15.62	9.02
09/30/82	5.00	65.17	0.61	1.33	8.88	19.01	6.68
10/03/82	5.37	68.78	0.53	1.44	10.00	13.88	6.94
10/07/82	5.13	67.59	0.51	1.32	9.62	15.83	7.29
10/10/82	5.40	70.05	0.58	1.38	9.58	13.01	6.94
10/13/82	5.23	67.65	0.60	1.24	9.53	15.75	7.69
03/19/83	5.14	67.50	0.56	1.48	8.79	16.53	5.94
03/22/83	5.18	67.49	0.58	1.42	9.97	15.36	7.02
03/26/83	5.04	66.41	0.54	1.47	9.71	16.83	6.61
03/12/84	5.01	63.52	0.63	1.29	11.39	18.16	8.83
03/16/84	5.27	69.65	0.58	1.57	10.34	12.59	6.59
03/19/84	5.16	67.19	0.59	1.52	9.52	16.02	6.26

SLAG ANALYSIS (BY C-E/KDL)

Slag Samples Removed from Corrosion Probes

KDL Sample Number	0498-M T-22 Deposit Ring #324	0499-M T-22 Deposit Rings #337	0500-M SA-210 Deposit Ring #325
Ash Composition:			
SiO_2	12.6	12.6	14.5
Al_2O_3	5.2	4.6	5.5
Fe_2O_3	61.9	58.3	60.1
CaO	4.4	4.2	5.4
MgO	0.6	0.8	0.9
Na_2O	0.5	0.8	0.5
K_2O	0.2	0.3	0.3
TiO_2	0.3	0.3	0.4
SO_3	9.8	N.D.	7.2
TOTAL:	95.5%	81.9%	94.8%

N.D. = Not Determined

The following pages report the analysis of slag deposits that were removed from several corrosion probe coupons (test rings) following exposure in the furnace. The analyses was performed by C-E's KDL laboratory.

The samples are identified as follows:

KDL Sample Number	Description
0498	T-22 Deposit Ring No. 324
0499	T-22 Deposit Ring No. 337
0500	SA-210 Deposit Ring No. 325

X-Ray Diffraction (XRD) Results:

The iron species were split between Fe_2O_3 (hematite) and Fe_3O_4 (magnetite).

The remaining species as selected by computer search were SiO_2 (quartz) and calcium silicate ($CaSiO_3$). Another possible species according to the "d" spacing data could be $CaSO_4$.

Sample #0498 contained some lines indicating the presence of Na_2SO_4 and Al_2SiO_5.

However, the magnitude of SO_3 reported could not be absolutely accounted for by the results of the XRD analysis, i.e., a highly reliable identification of a sulfur containing species could not be made.

The XRD patterns were examined for the presence of the species: $K_3Fe(SO_4)_3$, $Na_3Fe(SO_4)_3$, $K_2S_2O_7$ and $Na_2S_2O_7$. However, a calculation based on the alkali content (Na, K) showed that the maximum possible concentration for these species are near or below the detection limits previously established for these compounds.

Note: Sulfur content of sample #0498 as determined by X-Ray Flourescence (XRF) was:

$S = 6.5\%$

$SO_3 = 15.8\%$

Report of x-ray diffraction analysis:

Analysis Date: 3/15/83
Sample: KDL #0498

Major Phases: > = 30 percent

PDF	Formula
	None Found

Minor Phases: (10-30) percent

PDF	Formula
130534	Fe_2O_3
190629	Fe_3O_4

Trace Phases: < 10 percent

PDF	Formula
050490	SiO_2

PDF	Name	
50490	Silicon Oxide/Quartz	Low
130534	Iron Oxide/Hematite	Syn
190629	Iron Oxide/Magnetite	Syn

None Found: Elemental concentrations and/or line intensities do not indicate compound percentages that fall in the concentration range indicated.

These results were obtained by a combination of the output from the Johnson/Vand computer search/match program (Version 20) and evaluation by the x-ray diffractionist.

Report of x-ray diffraction analysis:

Analysis Date: 3/15/83
Sample: KDL #0499

Major Phases: > = 30 percent

PDF Formula
None Found

Minor Phases: (10-30) percent

PDF	Formula
130534	Fe_2O_3
190629	Fe_3O_4

Trace Phases: < 10 percent

PDF	Formula
050490	SiO_2

PDF	Name	
50490	Silicon Oxide/Quartz	Low
130534	Iron Oxide/Hematite	Syn
190629	Iron Oxide/Magnetite	Syn

None Found: Elemental concentrations and/or line intensities do not indicate compound percentages that fall in the concentration range indicated.

These results were obtained by a combination of the output from the Johnson/Vand computer search/match program (Version 20) and evaluation by the x-ray diffractionist.

Report of x-ray diffraction analysis:

Analysis Date: 3/15/83
Sample: KDL #0500

Major Phases: > = 30 percent

PDF Formula
None Found

Minor Phases: (10-30) percent

PDF	Formula
130534	Fe_2O_3
190629	Fe_3O_4

Trace Phases: < 10 percent

PDF	Formula
050490	SiO_2

PDF	Name	
50490	Silicon Oxide/Quartz	Low
130534	Iron Oxide/Hematite	Syn
190629	Iron Oxide/Magnetite	Syn

None Found: Elemental concentrations and/or line intensities do not indicate compound percentages that fall in the concentration range indicated.

These results were obtained by a combination of the output from the Johnson/Vand computer search/match program (Version 20) and evaluation by the x-ray diffractionist.

Independent analysis by ER&E, of slag removed from the right wall (near the front right corner) during the February, 1984 outage is reported on the following page.

The sample is essentially all mineral matter with very little carbon or moisture. The high SiO_2 content of the ash probably accounts for the wide temperature spread between the Initial Deformation (ID) and Fluid points. It is well known that SiO_2 tends to increase slag viscosity. The Na_2O content of 2.4% is higher than normal. It is apparently associated with the silica since there is only sufficient sulfur present to account for 0.37% Na_2O as the sulfate. The SiO_2/Al_2O_3 ratio of 3.08 would be interpreted by some as indicating a highly abrasive coal.

UTAH POWER AND LIGHT CO. - HUNTER 2 - CASTLE DALE, UTAH - WALL SLAG

Sample: 079709 66855-UPL

	Analyzed	Dry
Moisture	0.19	
Ash	99.66	99.84
SO_3 Free Ash	99.36	99.54
Carbon (EC12)	0.077	0.077
Sulfur, Total (IR)	0.19	0.19
Ash Alkali (as $\%Na_2O$)	3.23	3.23

ASH ELEMENTS (DRY) WT%

	SiO_2	Al_2O_3	P_2O_5	TiO_2	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Total	Diff.
w/SO_3	61.71	20.04	0.29	0.99	0.87	6.59	1.54	1.23	2.43	0.30	98.99	1.01
w/o SO_3	62.53	20.31	0.29	1.00	3.92	6.68	1.56	1.25	2.46			

Quality Factors	
B/A Ratio	0.1893
Slagging Index	0.0353
Foul Index	0.4599
Dolomite Ratio	0.5192
Fe_2O_3/CaO	0.5873
Si/Al	3.08
Silica Value	0.8372
Temp or Vis	2620

ASH FUSSION TEMPERATURES (°F)

	ID	H=W	H=W/2	Fluid
Reducing	2260	2345	2420	2640
Oxidizing	2310	2390	2480	2680

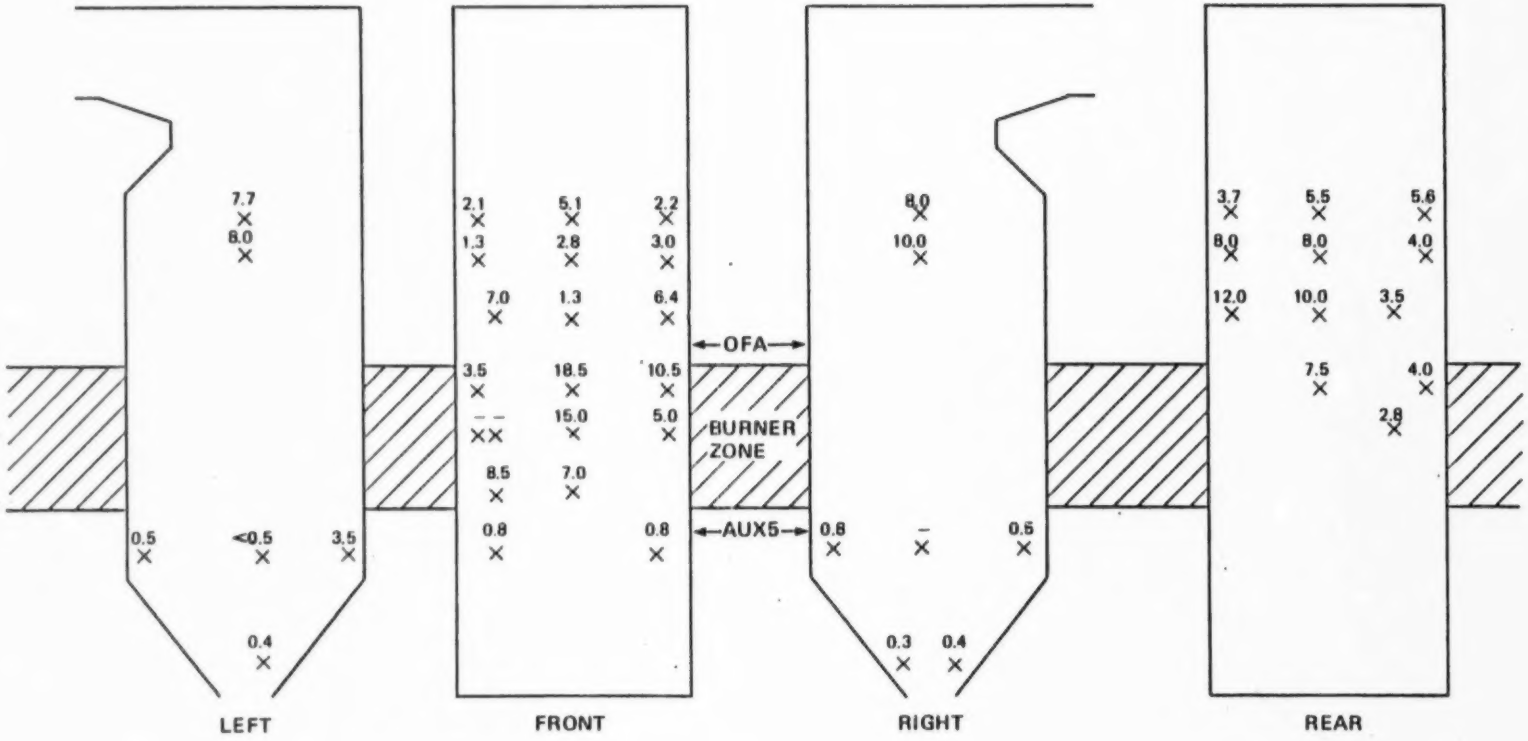
APPENDIX VII

FURNACE GAS TAP DATA

The following eight figures show all four walls of the boiler (unfolded) as seen by an observer standing outside the boiler and facing each wall. The "x"s indicate locations where furnace gas was sampled (gas taps) and analyzed. The numbers above the gas taps indicate the oxygen or carbon monoxide readings for the test as described in the title of each figure.

Figure J/VII–1

HUNTER UNIT NO. 2 GAS TAP OXYGEN LEVELS, TEST #1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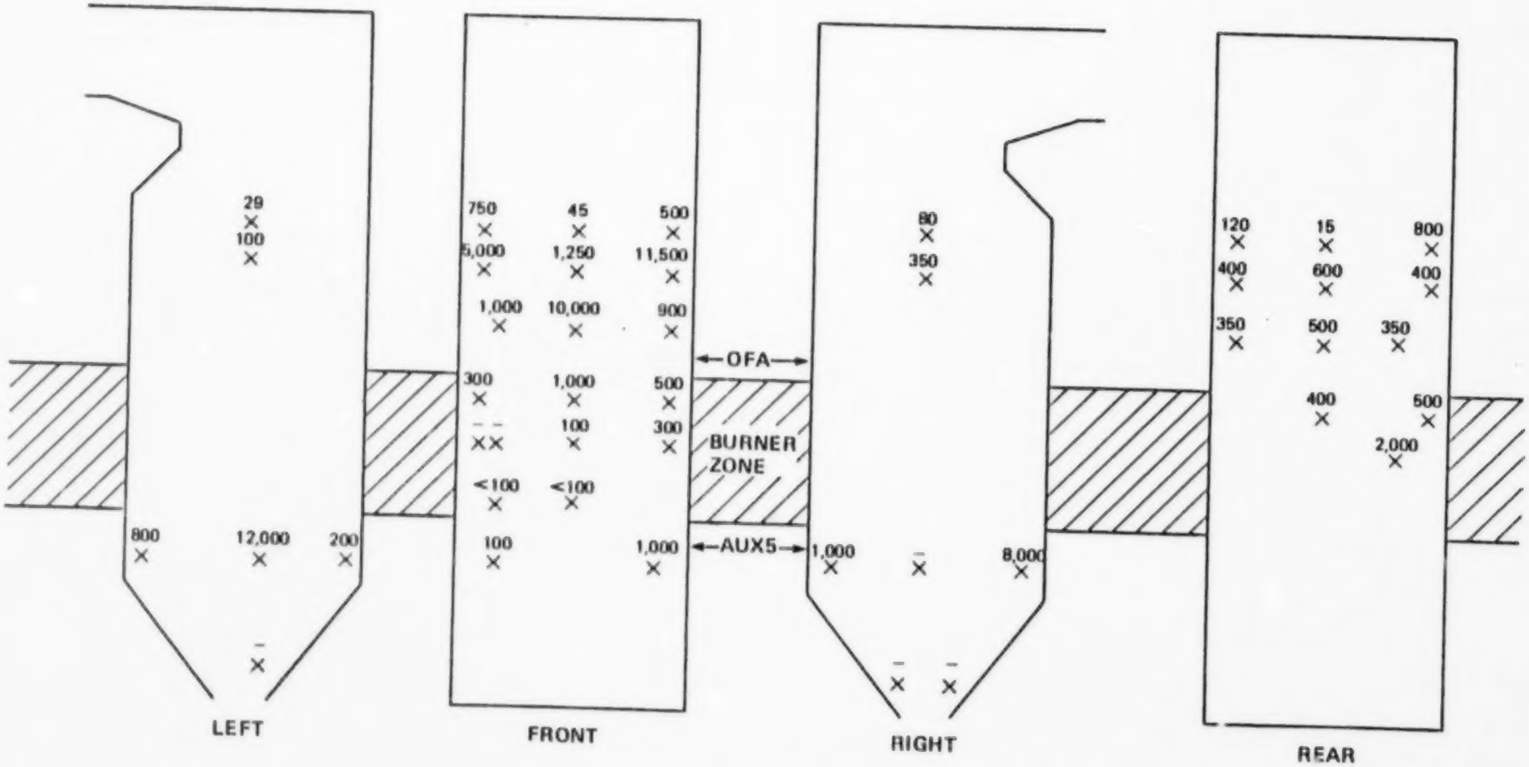
<0.5
3.5
0.4
LEFT
2.1
5.1
2.2
1.3
2.8
3.0
7.0
1.3
6.4
3.5
18.5
10.5
– –
15.0
5.0
8.5
7.0
0.8
0.8
FRONT
OFA
BURNER ZONE
AUX5
8.0
10.0
0.8
–
0.5
0.3
0.4
RIGHT
3.7
5.5
5.6
8.0
8.0
4.0
12.0
10.0
3.5
7.5
4.0
2.8
REAR

Figure J/VII-2

HUNTER UNIT NO. 2 GAS TAP CO LEVELS, TEST #1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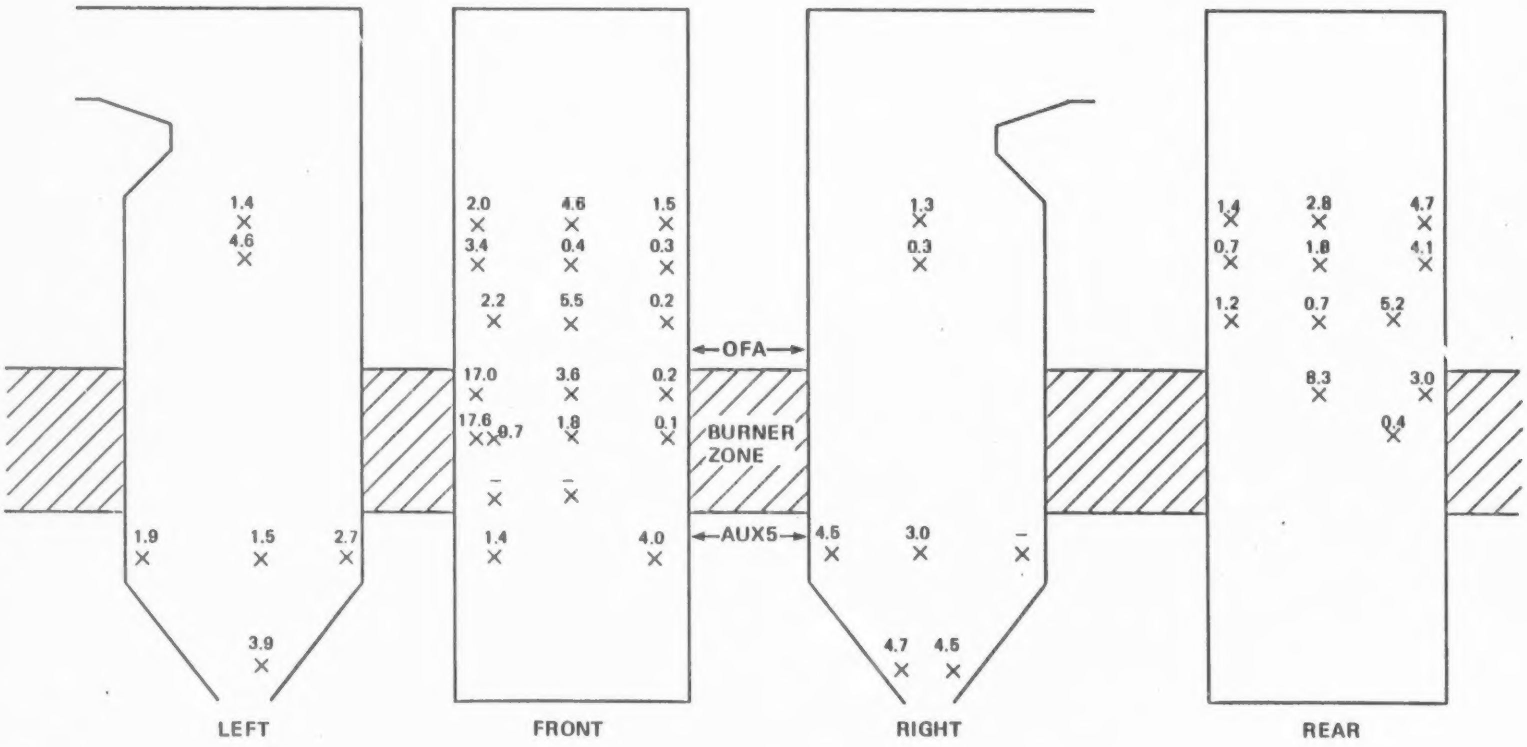
800
12,000
200
FRONT
750
45
500
5,000
1,250
11,500
1,000
10,000
900
300
1,000
500
100
300
<100
<100
100
1,000
OFA
BURNER ZONE
AUX5
RIGHT
80
350
1,000
8,000
REAR
120
15
800
400
600
400
350
500
350
400
500
2,000

Figure J/VII–3

HUNTER UNIT NO. 2 GAS TAP OXYGEN LEVELS, TEST #2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1.5
2.7
3.9
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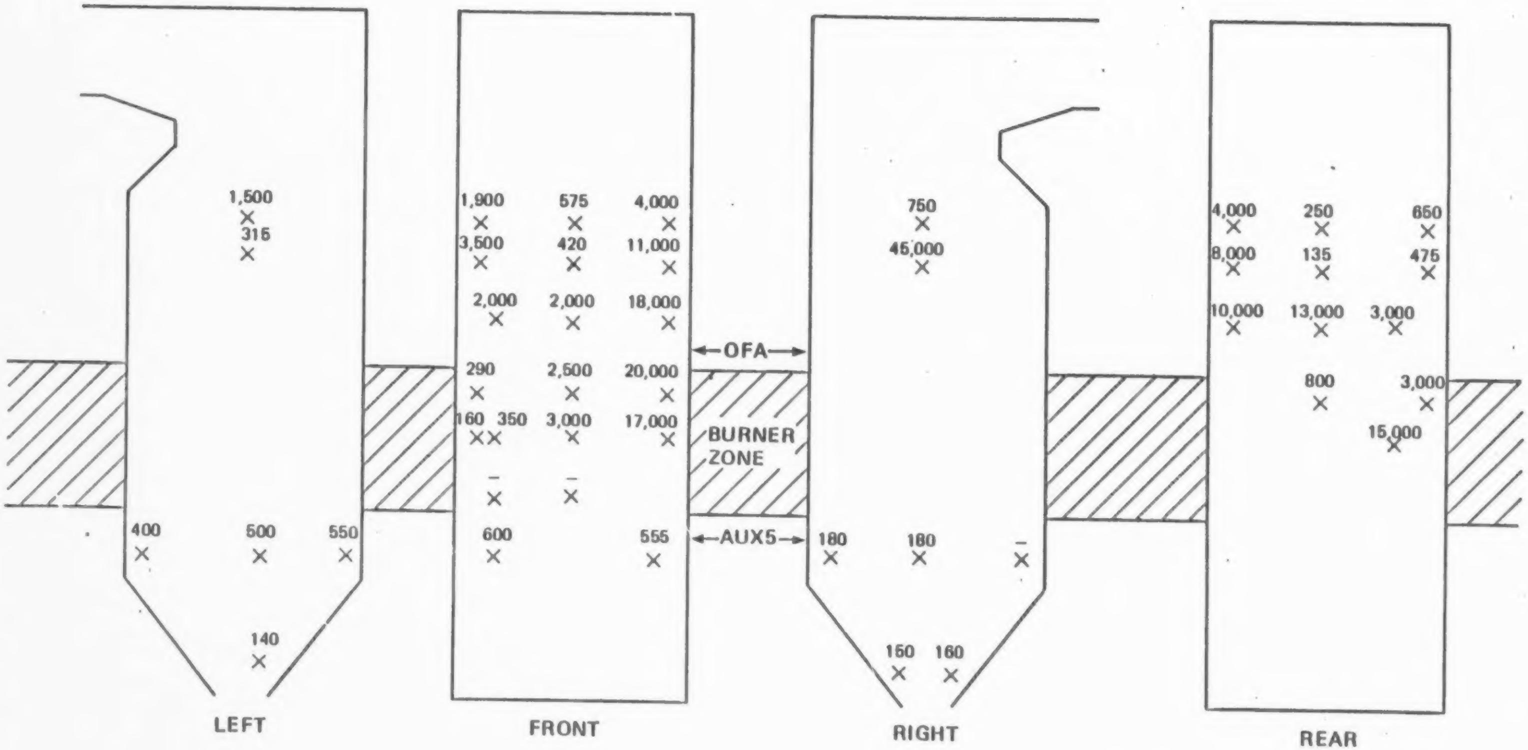
4.6
1.5
3.4
0.4
0.3
2.2
5.5
0.2
17.0
3.6
0.2
17.6
9.7
1.8
0.1
–
–
1.4
4.0
FRONT
OFA
BURNER ZONE
AUX5
1.3
0.3
4.5
3.0
–
4.7
4.5
RIGHT
1.4
2.8
4.7
0.7
1.8
4.1
1.2
0.7
5.2
8.3
3.0
0.4
REAR

Figure J/VII–4

HUNTER UNIT NO. 2 GAS TAP CO LEVELS, TEST #2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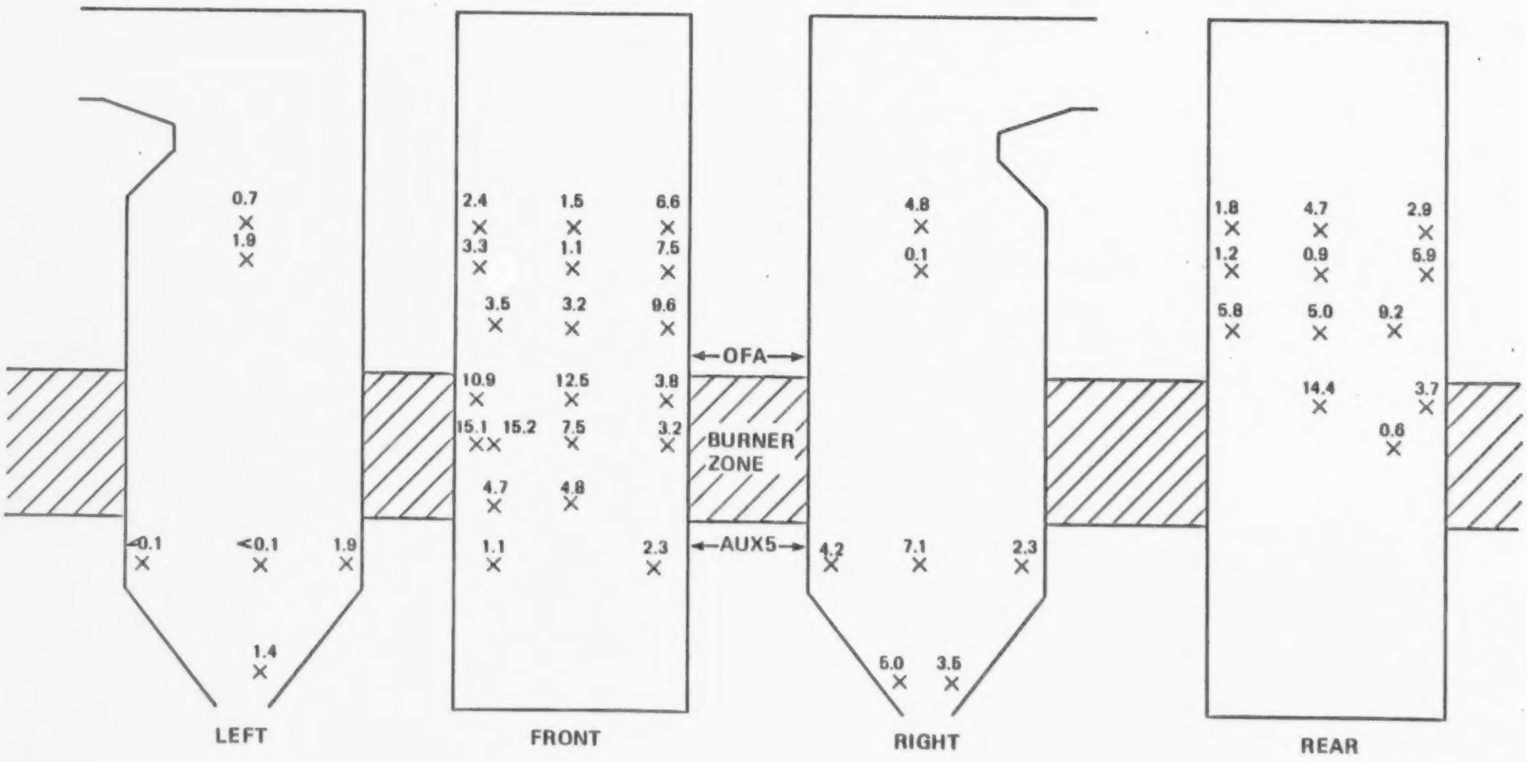
315
400
500
550
140
LEFT
1,900
575
4,000
3,500
420
11,000
2,000
2,000
18,000
290
2,500
20,000
160
350
3,000
17,000
–
–
600
555
FRONT
OFA
BURNER ZONE
AUX5
750
45,000
180
180
–
160
160
RIGHT
4,000
250
650
8,000
135
475
10,000
13,000
3,000
800
3,000
15,000
REAR

Figure J/VII–5

HUNTER UNIT NO. 2 GAS TAP OXYGEN LEVELS, TEST #3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<0.1
1.9
1.4
LEFT
2.4
3.3
3.5
10.9
15.1
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4.7
1.1
1.5
1.1
3.2
12.5
7.5
4.8
6.6
7.5
9.6
3.8
3.2
2.3
FRONT
OFA
BURNER ZONE
AUX5
4.8
0.1
4.2
7.1
2.3
5.0
3.5
RIGHT
1.8
1.2
5.8
4.7
0.9
5.0
14.4
2.9
5.9
9.2
3.7
0.6
REAR

Figure J/VII–6

HUNTER UNIT NO. 2 GAS TAP CO LEVELS, TEST #3

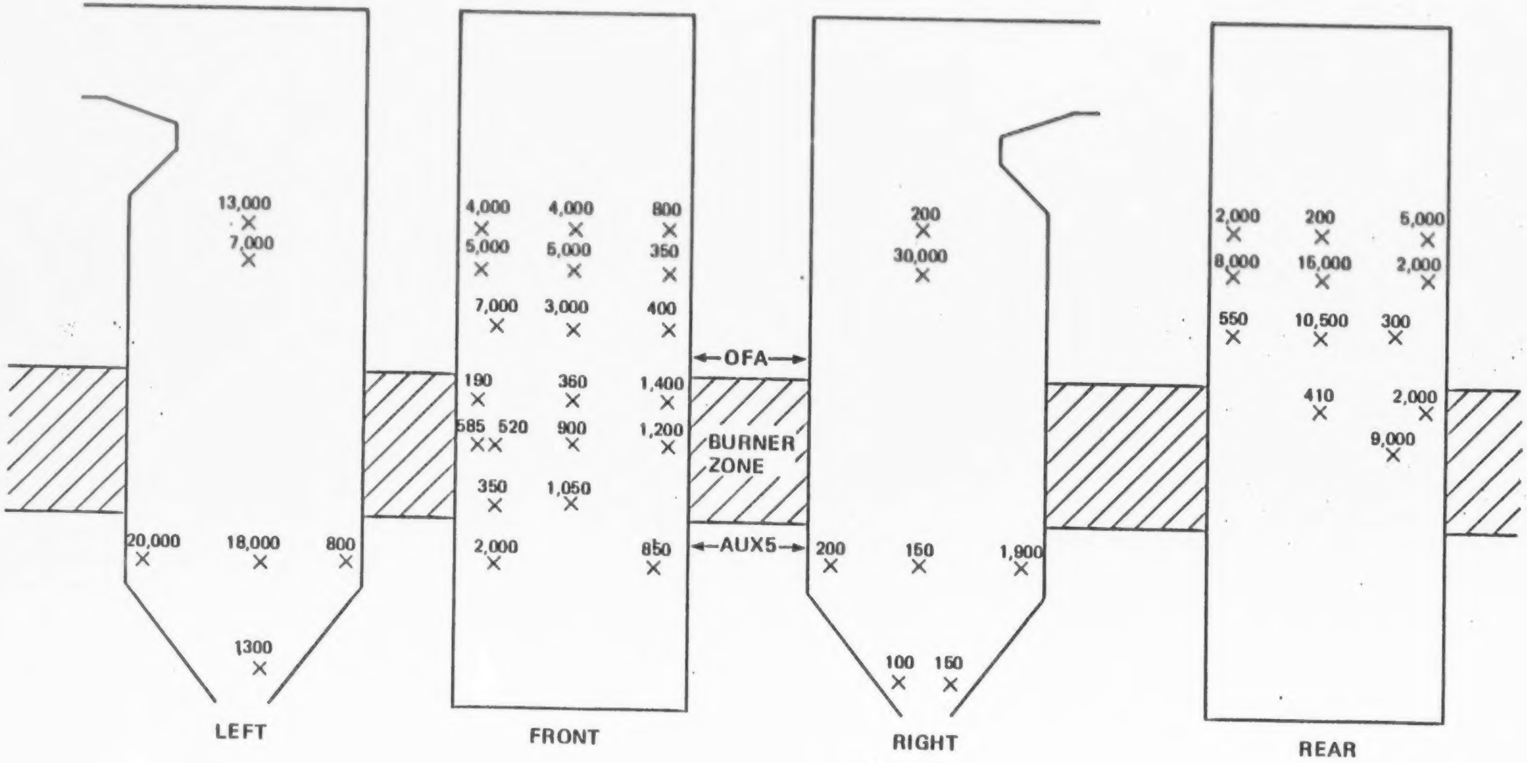
13,000
7,000
20,000
18,000
800
1300
LEFT
4,000
5,000
7,000
190
585
520
350
2,000
4,000
5,000
3,000
360
900
1,050
800
350
400
1,400
1,200
850
FRONT
OFA
BURNER ZONE
AUX5
200
30,000
200
150
1,900
100
150
RIGHT
2,000
8,000
550
200
15,000
10,500
410
5,000
2,000
300
2,000
9,000
REAR

Figure J/VII-7

HUNTER UNIT NO. 2 GAS TAP OXYGEN LEVELS, TEST #4

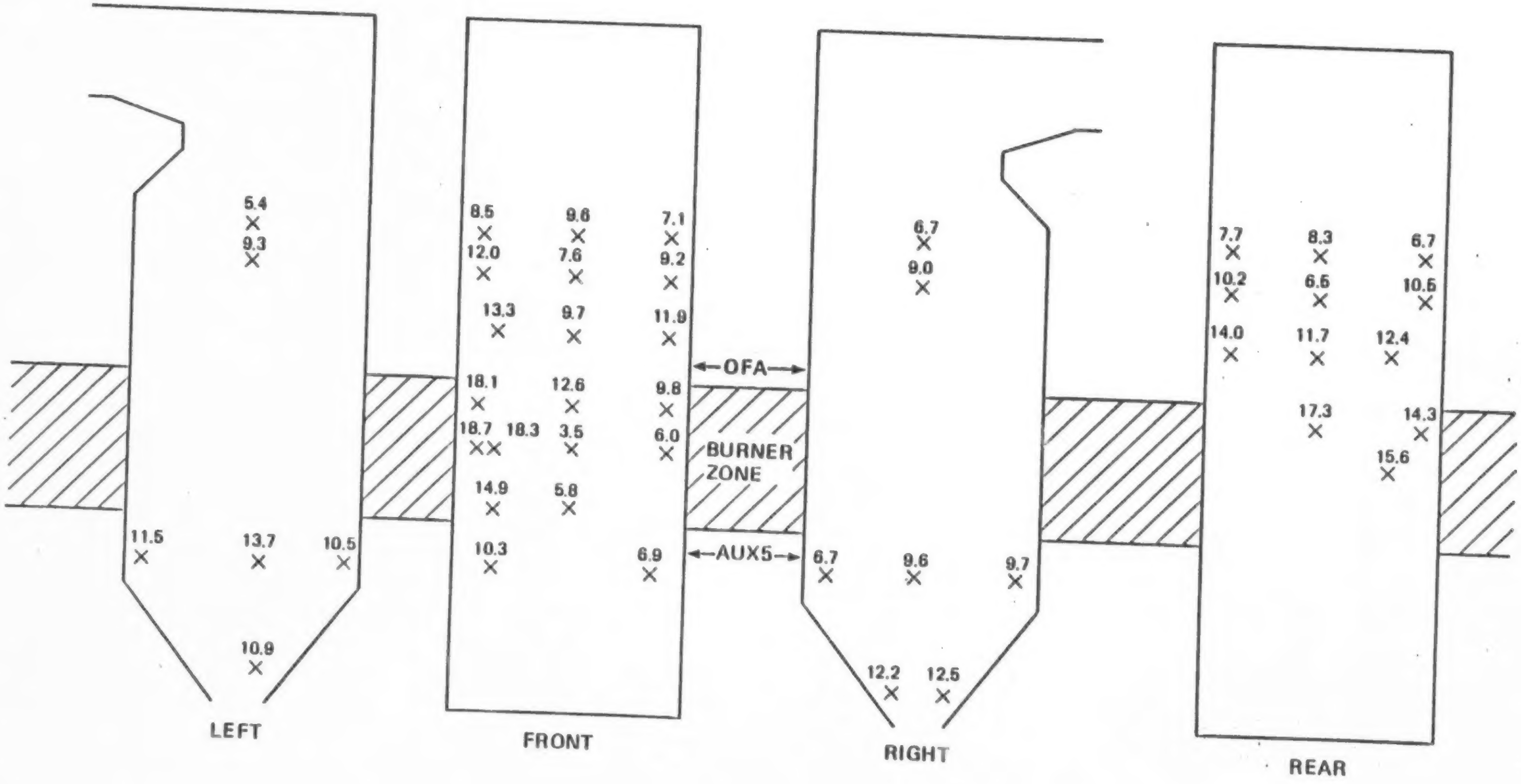
5.4
9.3
11.5
13.7
10.5
10.9
LEFT
8.5
9.6
7.1
12.0
7.6
9.2
13.3
9.7
11.9
18.1
12.6
9.8
18.7
18.3
3.5
6.0
14.9
5.8
10.3
6.9
FRONT
OFA
BURNER ZONE
AUX5
6.7
9.0
6.7
9.6
9.7
12.2
12.5
RIGHT
7.7
8.3
6.7
10.2
6.5
10.5
14.0
11.7
12.4
17.3
14.3
15.6
REAR

Figure J/VII–8

HUNTER UNIT NO. 2 GAS TAP CO LEVELS, TEST #4

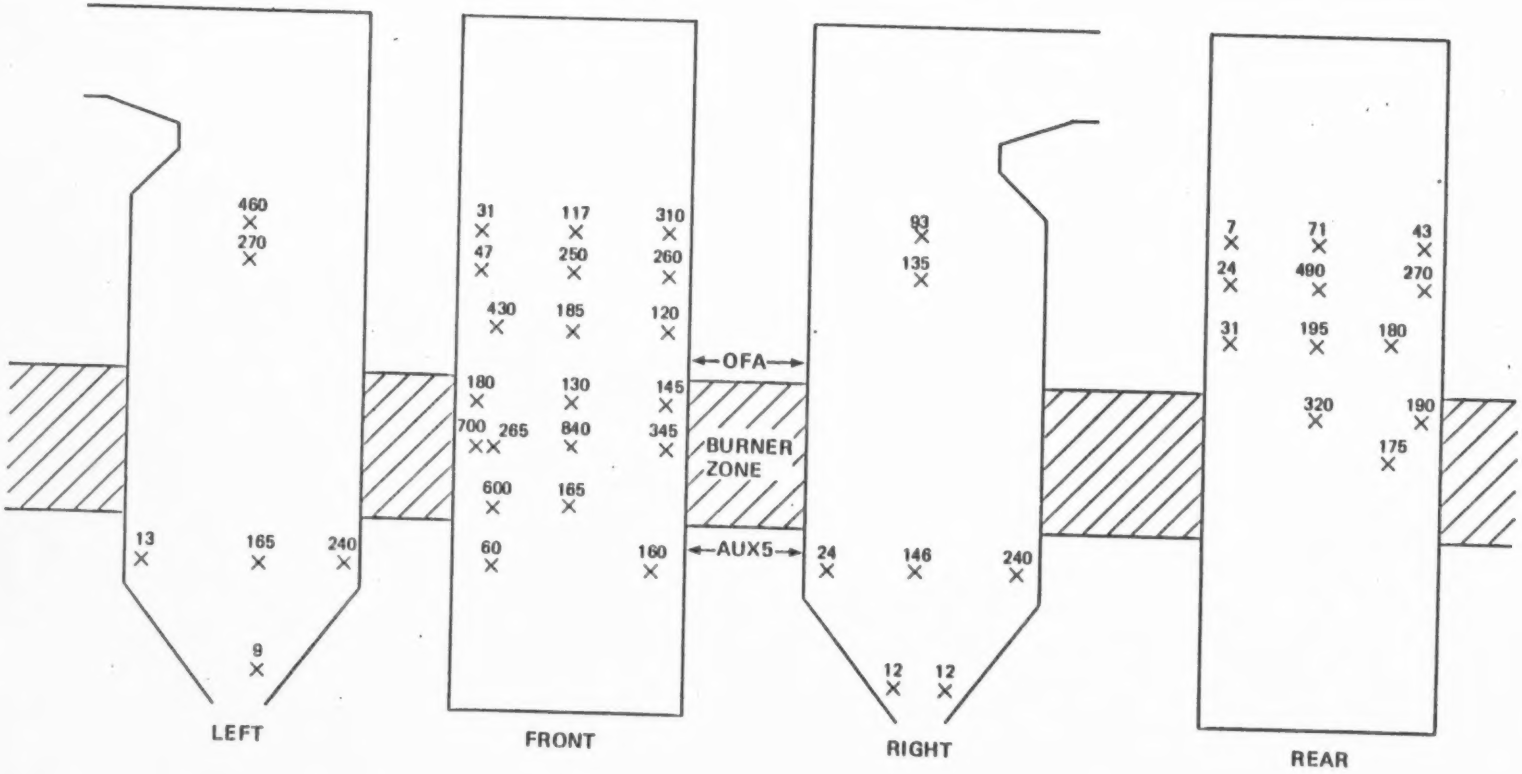
460
270
13
165
240
9
LEFT
31
47
117
250
310
260
430
185
120
180
130
145
700
265
840
345
600
165
60
160
FRONT
OFA
BURNER ZONE
AUX5
93
135
24
146
240
12
12
RIGHT
7
24
31
71
490
195
320
43
270
180
190
175
REAR

TABLE J/VII-1

LIMITED GAS TAP DATA
HUNTER UNIT NO. 2, TEST NO. 5(1)

Characterization Test No.	Offset Angle	Gaseous Component	Gas Tap Locations(2)					
			17	18	19	23	24	25
182 (11/17/81)	17°	O_2 (%)	14.1	13.9	14.0	18.0	17.1	13.7
		CO (vppm)	379	429	292	489	814	495
		NO_x (vppm)	197	246	187	63	116	186
		CO_2 (%)	5.42	6.01	5.28	1.90	2.66	5.46
184 (11/17/81)	33°	O_2 (%)	17.4	14.0	16.4	20.7	20.2	16.0
		CO (vppm)	684	246	606	80	322	739
		NO_x (vppm)	165	285	112	9	54	125
		CO_2 (%)	3.75	6.52	2.70	0.37	1.23	3.04
185 (11/17/81)	25°	O_2 (%)	16.3	13.4	16.4	19.8	17.8	15.8
		CO (vppm)	>1176	356	741	326	391	699
		NO_x (vppm)	157	290	112	15	49	132
		CO_2 (%)	3.68	6.25	2.82	0.58	1.24	3.60

- No OFA
- 20% FAD
- Btilt ~+19°
- Flue Gas O_2 ~6.0%
- Flue Gas CO ~50 vppm
- Load ~420 MW_e

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(1) Initial gas tap testing was performed to evaluate the wall atmospheres above and below the top level of burners.

(2) See Figure B-5 (in Part B of this report) for locations of gas taps.